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A SYSTEM FOR USING RADAR TO RECORD WAVE DIRECTION.(U)
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A System for Using Radar to Record Wave Direction

LEVEL II

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by

M.G. Mattie and D.L. Harris

TECHNICAL REPORT NO. 79-1
SEPTEMBER 1979

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Radar	Wave direction	Wave refraction	Waves

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A radar system that provides images of waves in the coastal zone to obtain wave direction information is described. The heart of the system is an X-band marine radar which operates at 9,375 megahertz with a 3-centimeter wavelength and a 0.05-microsecond pulse width. The records are accumulated by photographing the plan position indicator (PPI) scope.

The system is designed for unattended operation and includes an automation unit that activates the radar at preset times, usually at 2-hour intervals. A

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sequence of one to nine photos is obtained on each of four ranges after which the system turns off until the next scheduled observation.

Wave images show single and multiple long-crested wave trains permitting observation of wave refraction and shoaling. The information content in the radar images is similar to that in aerial photos. However, radar images can be collected at night, during overcast, and in light rain conditions. Radar imagery is more limited than aircraft imagery in geographical coverage and in the quality of the imagery.

Good agreement was found between estimates of wave direction and length obtained with radar and those obtained with other observational techniques.

PREFACE

This report is published to provide coastal engineers with the results of a project to develop a radar device that will automatically collect wave direction information at coastal sites. The work was carried out under the coastal hydraulics research program of the U.S. Army Coastal Engineering Research Center (CERC).

This report was prepared by Mr. Michael G. Mattie, Physicist, and Dr. D. Lee Harris, Chief, Coastal Oceanography Branch, CERC.

The development of the CERC radar system was accomplished through the advice and support of many people and several organizations. Particular recognition is given to CWO L. Brown of the U.S. Coast Guard Research and Development Center; C. McKinney, Pacific Missile Test Center, who assembled the CERC system; C. Gable who monitored the radar system assembly; and J. Dayton who provided photographic services. Thanks are also extended to Dr. O. Shemdin of the Jet Propulsion Laboratory for providing the West Coast Experiment data.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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FIGURES--Continued

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

A SYSTEM FOR USING RADAR TO RECORD WAVE DIRECTION

by
M.G. Mattie and D.L. Harris

I. INTRODUCTION

The Coastal Engineering Research Center (CERC) and the Beach Erosion Board (BEB) (predecessor to CERC) have collected wave data along the U.S. coasts for nearly 30 years. Although a wealth of statistics on wave height and period and thousands of wave spectra have been obtained, few measurements of wave direction have been made. Information on wave direction is needed for the estimation of longshore sand transport, harbor design, and the solution of other coastal engineering problems. Many techniques for recording wave direction have been proposed and tested but none have been entirely satisfactory.

This report discusses a technique for recording wave direction, based on the use of imaging radar. Ijima, Takahashi, and Sasaki (1964) and Wright (1965) were probably among the first to report the use of radar for imaging ocean waves. Oudshoorn (1960), Wills and Beaumont (1971), Evmenov, et al. (1973), and others have reported wave images obtained with radars similar to those used in the experiments described in this report. However, it is not known whether any of these authors attempted to develop imaging radar as an operational tool for collecting wave information.

Radar may be used to image the prominent wave crests in a wave field (when conditions are suitable) by photographing the display scope (see Fig. 1). Figure 2 is an aerial photo of the same area shown in Figure 1. In general, radar images show many of the same characteristics as aerial photos and several distinct wave trains can often be identified. Although radar images are not as clear as aerial photos, they have the distinct advantage of being obtainable at night and during storms; an expensive platform (aircraft) is also unnecessary. Interpretation of the radar image is often as simple as that of a good aerial photo. The interpretation of aerial photos has been examined by McClenan and Harris (1975).

The CERC radar system is described in Section II as a wave data collection device. Samples of radar wave imagery and a data analysis system are presented in Section III. The essentials of radar theory and operation, needed for an understanding of the engineering characteristics of a wave data collection system, are discussed in Section IV. Section V compares the data on wave direction and length obtained by radar with that obtained by other methods.

Other procedures for using radar in the collection of wave data, including several proposed procedures for obtaining these data without radar are presented in Section VI. Section VII discusses additional capabilities of radar and future plans for its use. A summary highlighting the advantages and disadvantages of obtaining wave information with an X-band shore radar is presented in Section VIII.

Figure 1. CERC radar image of waves in the Mission Beach area, San Diego, California, taken 29 March 1977.

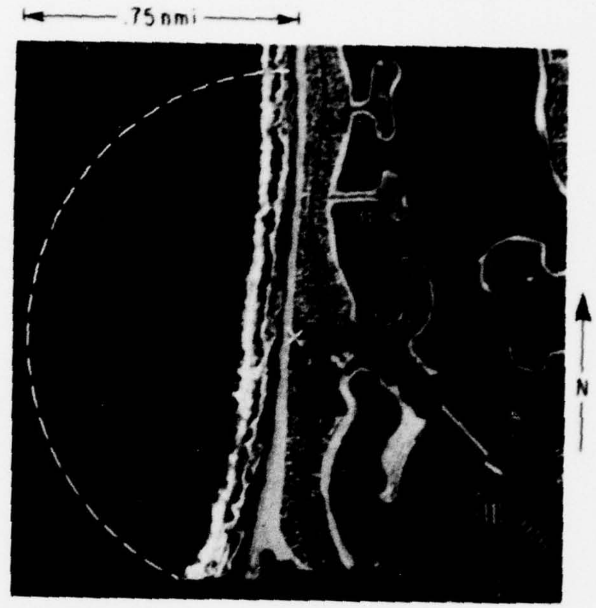

Figure 2. Aerial photo of the Mission Beach area, San Diego, California, taken 29 March 1977 by a NASA U-2 aircraft in support of the West Coast Experiment. CERC radar location is shown by X. (Same scale as Fig. 1.)

II. A SYSTEM FOR RECORDING WAVE DIRECTION BY RADAR

The CERC radar system has been assembled to automatically obtain wave images, and includes a Raytheon 1020/9XR Mariners Pathfinder X-band radar mounted in a van to provide mobility. A rotating antenna is mounted on the roof of the van (Fig. 3), or on a 2-meter (6.56 feet) mast at the end of the trailer for additional elevation. This radar has a pulse width of 0.05 microsecond (50 nanoseconds) with a range resolution of 10 to 20 meters (32.8 to 65.6 feet). The 2.74-meter (9 feet) slotted-array antenna gives a horizontal beam width of 0.9° at 3 decibels and has a rotation rate of 33 revolutions per minute. Pulses of electromagnetic energy with a nominal wavelength of 3 centimeters (nominal frequency 10^{10} hertz) are beamed over the water. A part of this energy is scattered back to the antenna by a process explained in Section IV. The back-scattered energy is displayed on a 10-inch-diameter cathode-ray tube (CRT) called a "plan position indicator" (PPI) in the form of light and dark patches which parallel the wave crests. Data are recorded by photographing the CRT using a Bolex 16-millimeter H-16 reflex camera. The PPI and camera are shown in Figure 4.

A CRT with a fast-decay phosphor is used. The standard CRT uses a medium- to slow-decay phosphor which retains the target for easy viewing. The fast phosphor is used for data collection to obtain sharp images with the time-lapse photography.

To adjust the radar to obtain wave images, the signal gain is increased for the weak sea clutter return to appear on the CRT. The scope intensity is kept low so the CRT is not saturated. Rain clutter and sea clutter controls are turned to a low position. The rain clutter control is used in the "just on" position to limit some of the strong return near the center of the scope which tends to saturate that part of the CRT. This gives better images in the surf zone while not affecting the return from the more distant wave areas.

The radius of the region displayed may be varied by discrete steps from 0.695 to 44.4 kilometers (0.375 to 24 nautical miles). The optimum radius or "range" for wave imaging varies with the ambient wave conditions—shorter ranges are best for shorter waves.

The CERC system is designed for unattended operation; an automation system turns on the radar at a periodic time interval that can be set from 1 to 9 hours. After a suitable warmup time (about 10 minutes) the radar signal is fed to the antenna as it scans the sea, and a sequence of 1 to 9 photos is obtained at each of four ranges, 0.695, 1.39, 2.78, and 5.56 kilometers (0.375, 0.75, 1.5, and 3 nautical miles).

The automation unit controls the opening and closing of the camera shutter and the sector of the sweep which is photographed. The system is then turned off until the next scheduled observation. Photos are taken at several ranges because the optimum range to obtain information on wave direction or length depends on the wavelength and height of the

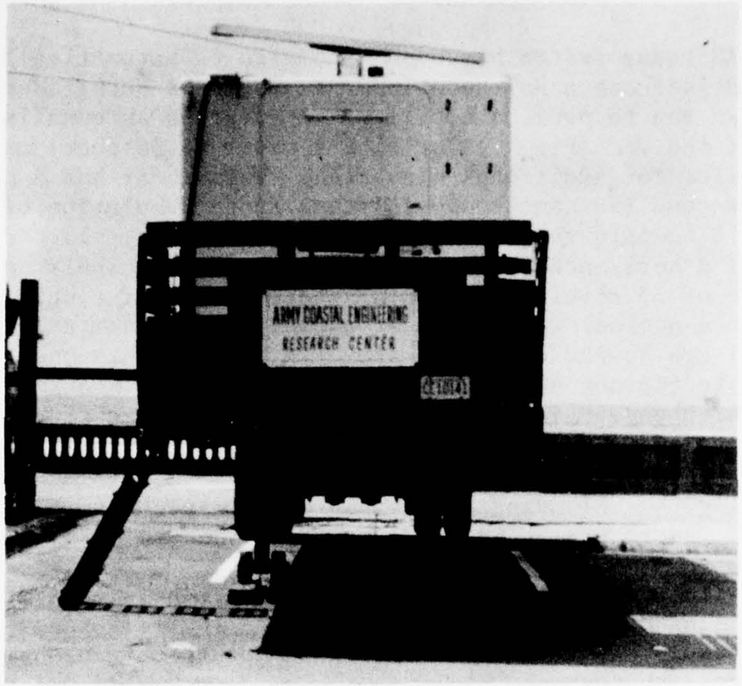

Figure 3. CERC radar system as deployed at Mission Beach, San Diego, California, during the West Coast Experiment in March 1977.

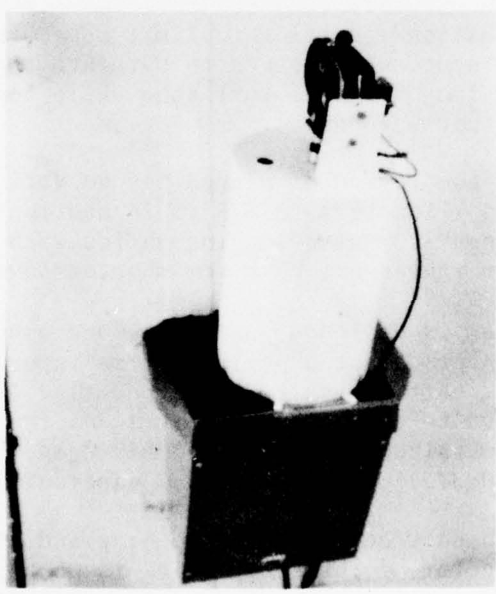

Figure 4. CERC radar system PPI and Bolex camera.

ambient waves. Multiple photos will permit the resolution of any 180° ambiguity about wave direction and will minimize the chance that the random selection of observation times will give misleading data. The system can be operated for prolonged periods with a constant range if desired. In the photographic mode the camera shutter is opened when the radar antenna sweep crosses from land to sea and remains open until the entire sea has been scanned. The shutter then closes and the film is advanced one frame. The duration of a 360° radar sweep is 1.82 seconds. Additional variation of parameters can be programed into the system if experience shows this to be desirable. Power to the radar antenna is shut off when the antenna is not facing the sea.

The unit has a clock which provides a time signal in hundredths of a second to the light emitting diodes (LED) on the PPI that document each photo. With normal operation, one roll of 16-millimeter film will last about 1 week. The developed film is analyzed in the CERC laboratory with the aid of a viewing device described in Section III.

III. RADAR RESULTS

Radar images of waves presented in this report were collected using two different radars. A short sequence of images was collected with a Decca radar during an experiment in January 1976 at Nauset Beach on Cape Cod, Massachusetts, to test the concept of using radar to provide wave direction information. The Decca radar was part of a vessel tracking system on loan from the U.S. Coast Guard Research and Development Center in Groton, Connecticut. All other radar images were obtained with the CERC radar system. For several months the CERC system regularly collected wave images in an automated mode at Channel Islands Harbor, California, in support of a sediment transport study. An additional set of images was collected at San Diego, California, with the CERC radar during 22 February to 31 March 1977 in support of the West Coast Experiment organized through the Jet Propulsion Laboratory (JPL), Pasadena, California. The Decca radar images clearly showed single and multiple wave trains, and led to the construction of the present CERC radar system.

This section shows the type of images available from the two radars and highlights some special features.

1. Images of Single and Multiple Wave Trains.

Figure 5 shows a PPI photo of a single wave train imaged by the Decca radar during the Cape Cod test. The wave train is from the east with a wavelength of 90 meters (295 feet) near the outer limit of the image. One disadvantage of the Decca radar is that when the gain is turned high enough to see the waves near the edge of the scope at 1.39 kilometers (0.75 nautical mile) from the radar, the surf area is saturated and the waves in the surf zone cannot be distinguished due to the bright return. The Raytheon radar in the CERC system handles this problem much more satisfactorily. Figure 6 is a photo of the PPI scope taken by the CERC radar in California at the 1.39-kilometer range, and shows one primary

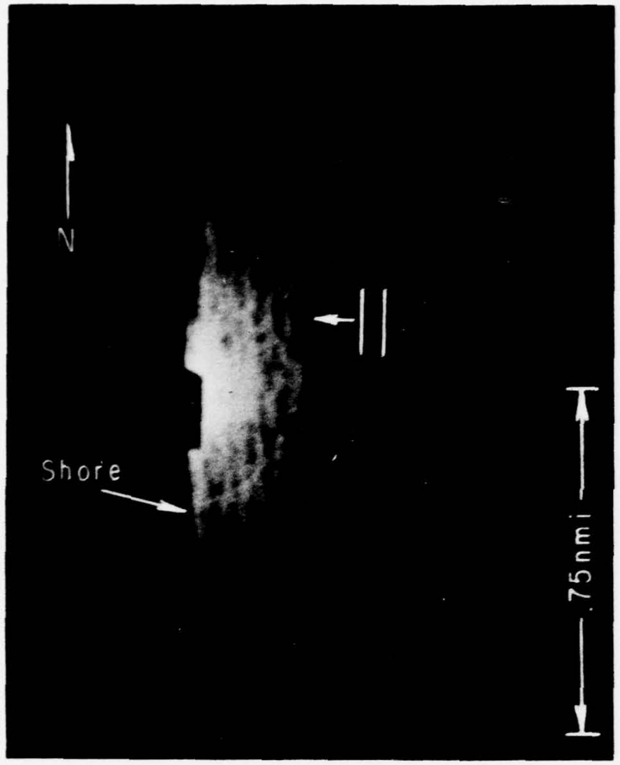

Figure 5. PPI photo of a single wave train imaged by the Decca radar. Photo taken 12 January 1976 at Cape Cod, Massachusetts.

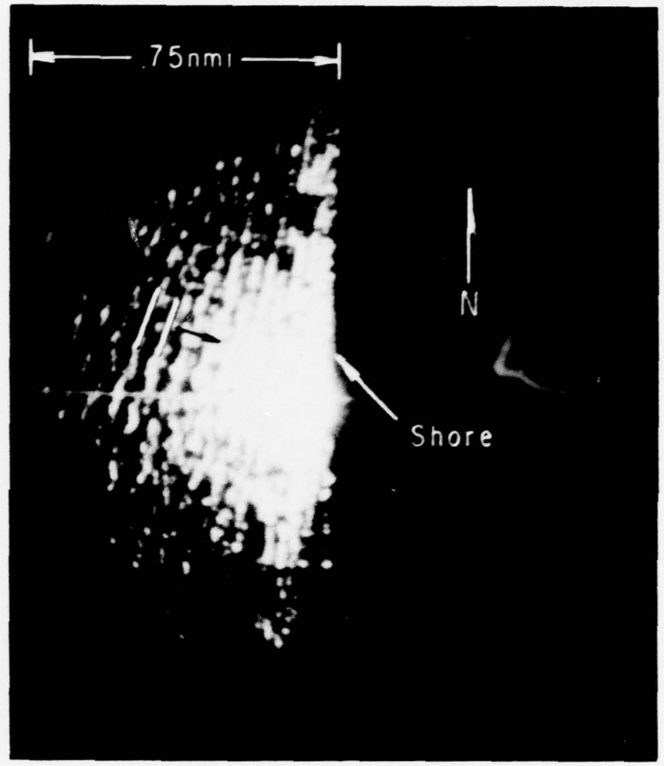

Figure 6. PPI photo of a single wave train imaged by the CERC radar. Photo taken March 1977 at Mission Beach, San Diego, California.

wave train. Waves in the surf zone are usually clearer with the CERC unit. Reproduction has unavoidably reduced the definition of the radar photos for this report.

Radar can also image multiple wave train conditions. Figure 7 from the CERC radar in California shows two wave trains (a swell from the southwest and a second wave train from west-northwest). Three wave trains can be seen in Figure 8 (also from the CERC radar). Single or multiple wave trains were seen in 80 to 90 percent of the PPI photos taken with the two radar systems; surf zone waves were seen in all the photos.

In the sequence of radar images in Figures 9 to 12, the radar return for the same location and sea conditions is shown for four different radar ranges. These images were all taken within a 2-hour period during the Cape Cod test. Good return was seen even on the 5.6-kilometer (3 nautical miles) range with waves obvious to at least 3.7 kilometers (2 nautical miles) from the radar.

2. Possible Measurements with Radar.

Since the CERC system takes an image of the wave field every radar sweep and the time between sweeps is recorded with LED's, the wave speed can be measured by noting the distance traveled by a particular wave between two frames. Figures 13, 14, and 15 show how this measurement of wave speed is determined. The figures show the radar return for identical conditions and settings, except that each image was taken 5.5 seconds later than the preceding one. In comparing these figures, the distance traveled by a particular wave can be measured (marked by arrows). A rough estimate of period can also be made since both Figures 13 and 15 show a wave just reaching the breakwater. The times on the photos indicate that the wave period is approximately 11 seconds.

By viewing a series of radar images taken over a longer time period, the evolution of the wave field can be documented (see Figs. 16 to 19 which were taken at approximately 4-hour intervals, and show that the wavelengths increase with time).

Refraction phenomena as imaged in radar photos can be compared with that predicted by refraction theory. Figures 20 and 21 show two cases of refraction as seen in radar images. Figure 20 taken at Torrey Pines, San Diego, California, shows strong bending of wave crests in the left of the image due to an underwater feature (Scripps Canyon). Figure 21 shows the bending of a wave train which occurs when deepwater wave crests approach the shore at an angle of approximately 45°. A short wave train due to a local wind from the northeast and a longer swell from the southeast also appear in the figure. Refraction is shown by arrows drawn perpendicular to the waves on each wave train at two different distances from shore. If the bathymetry is known, and the waves are not too high, it may also be possible to separate refraction due to the bottom from that due to currents.

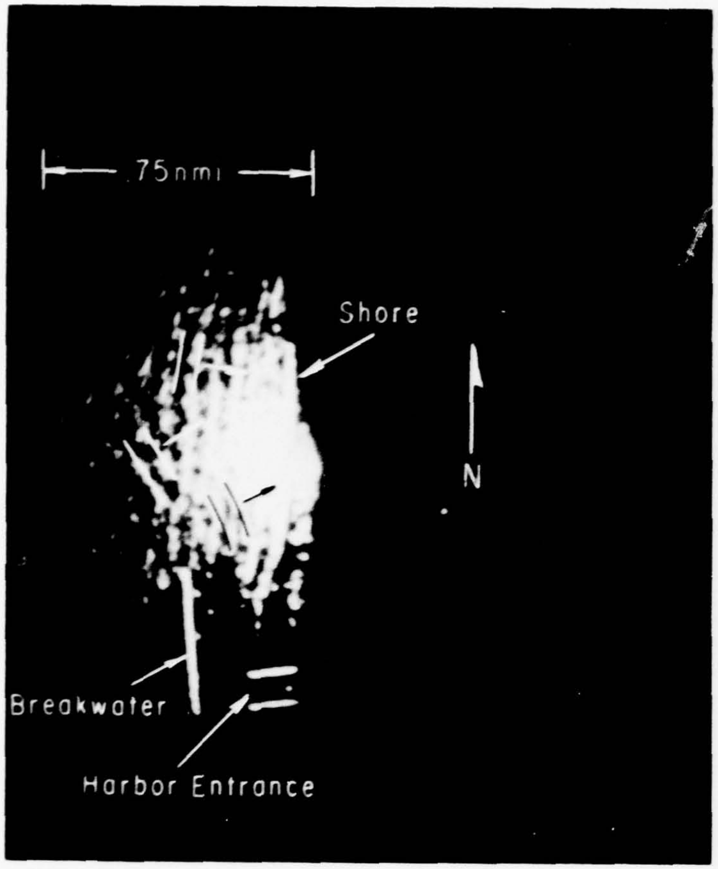

Figure 7. Two wave trains as seen by the CERC radar at Channel Islands Harbor, California. Note the long swell wave train from the southwest and a second shorter wave train from west-northwest.

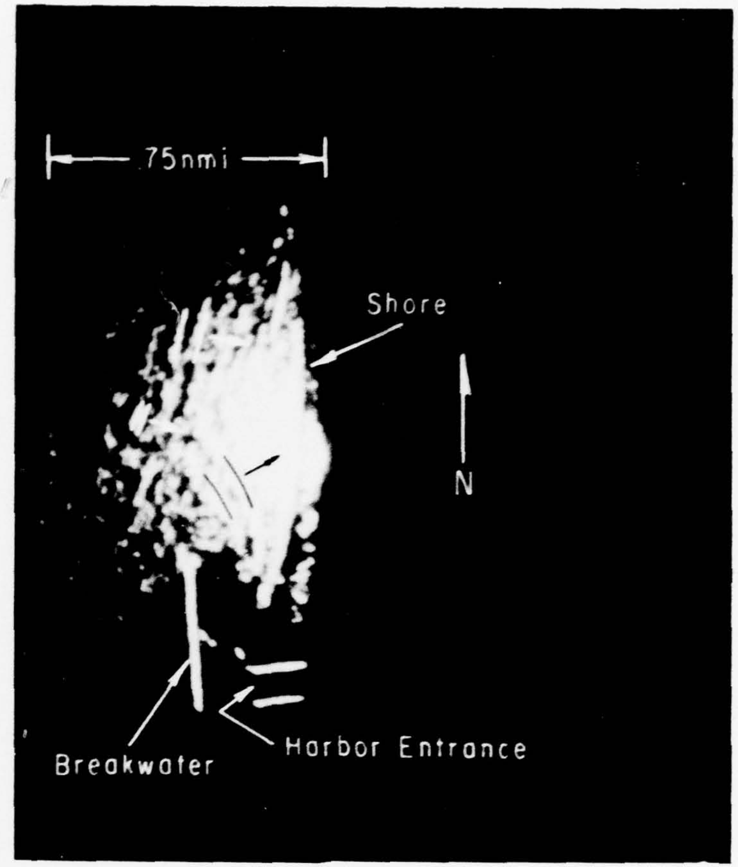

Figure 8. Three wave trains on a PPI photo taken at Channel Islands Harbor, California. Note swell from the southwest, a second wave train from the west-northwest, and a third short wave train due to local wind developing from the northwest.

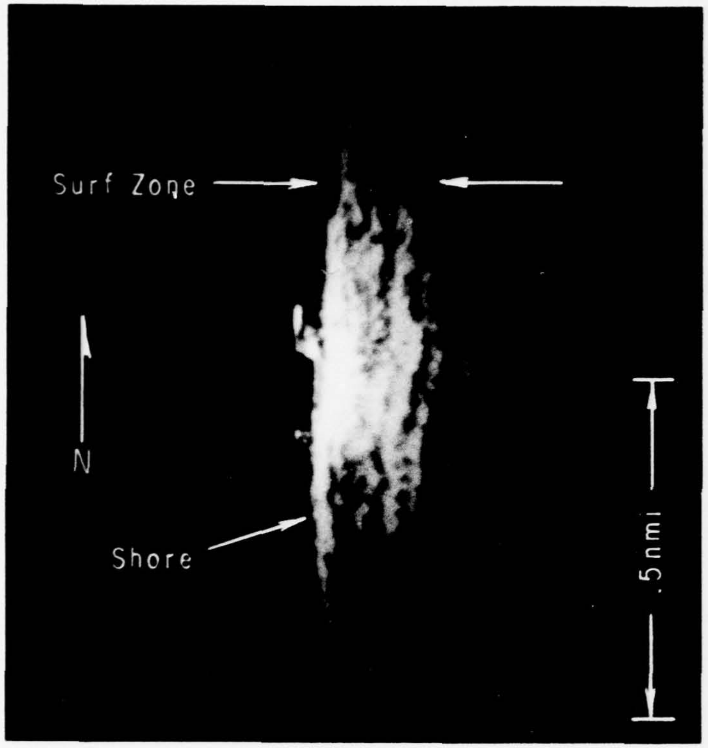

Figure 9. Radar wave image taken 12 January 1976 at Cape Cod, Massachusetts. Range is 926 meters (0.5 nautical mile).

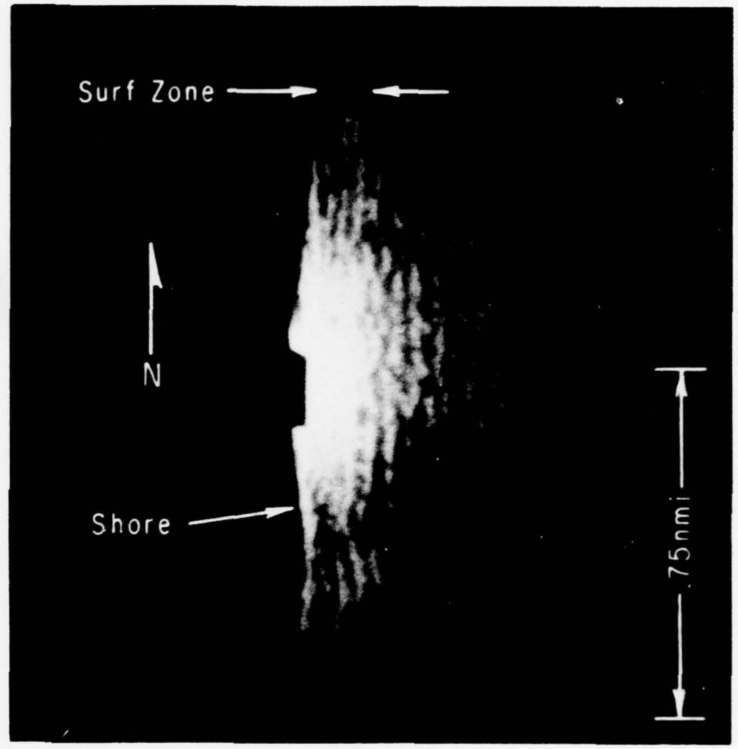

Figure 10. Radar wave image taken 12 January 1976 at Cape Cod, Massachusetts. Range is 1.39 kilometers (0.75 nautical mile).

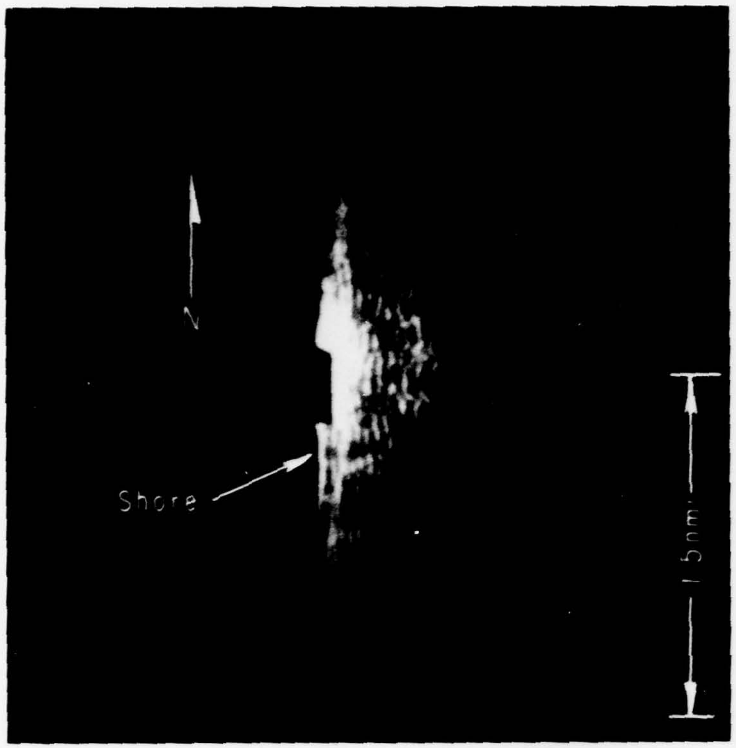

Figure 11. Radar wave image taken 12 January 1976 at Cape Cod, Massachusetts. Range is 2.78 kilometers (1.5 nautical miles).

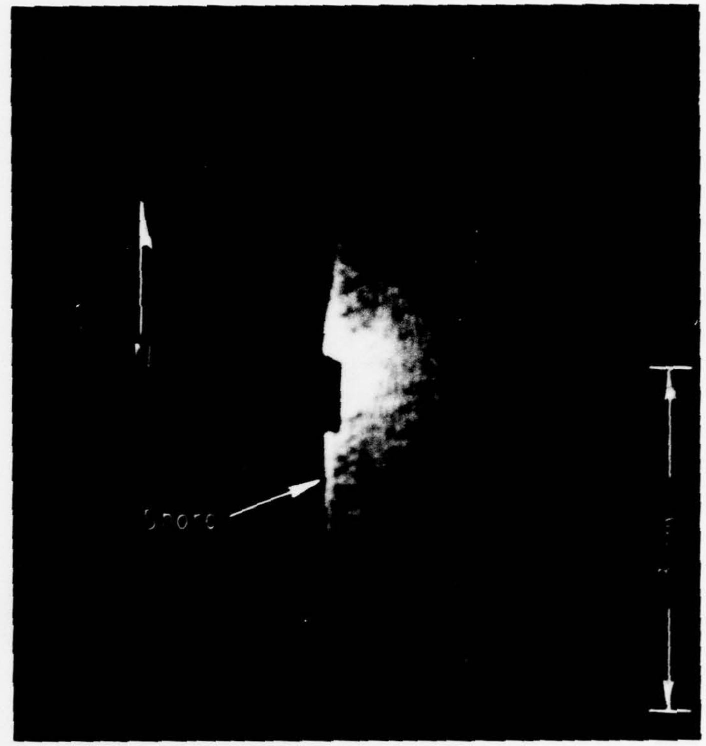

Figure 12. Radar wave image taken 12 January 1976 at Cape Cod, Massachusetts. Range is 5.56 kilometers (3 nautical miles).

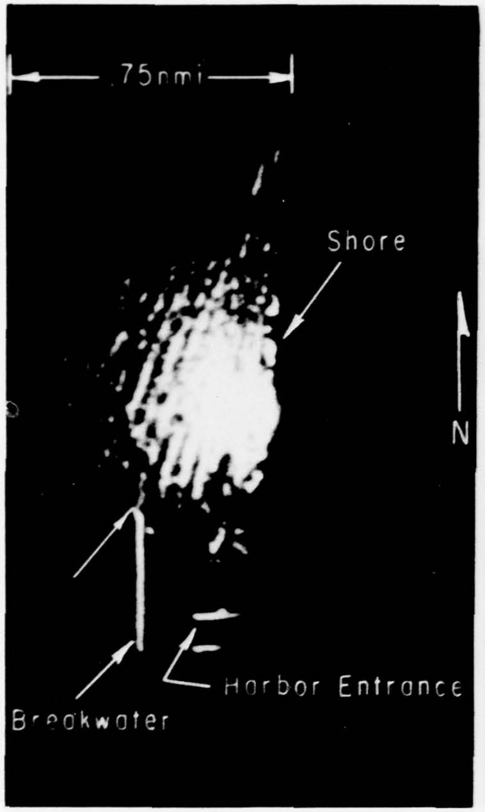

Figure 13. Radar wave image from Channel Islands Harbor, California, 29 April 1977. Note the long-crested wave at end of the breakwater shown by an arrow.

Figure 14. Radar wave image taken 5.5 seconds later of same area shown in Figure 13 (same long-crested wave is shown by arrow).

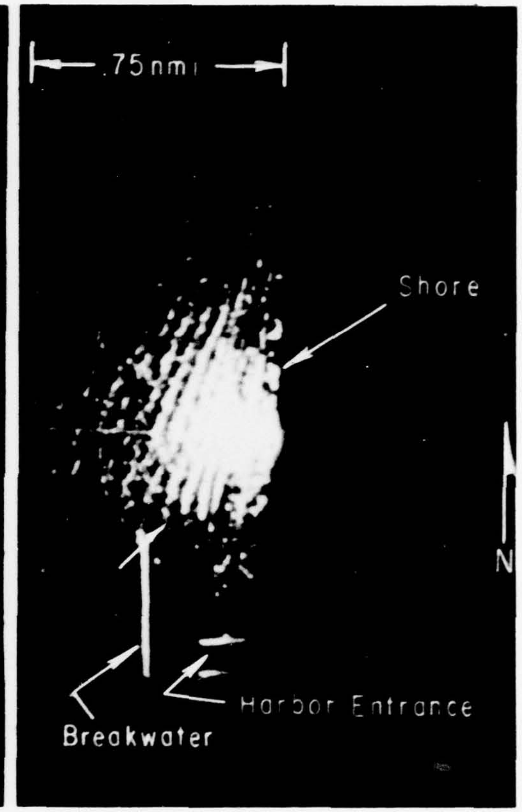

Figure 15. Radar wave image of same area taken 5.5 seconds after Figure 14 and 11 seconds after Figure 13 (note long-crested wave shown by arrow).

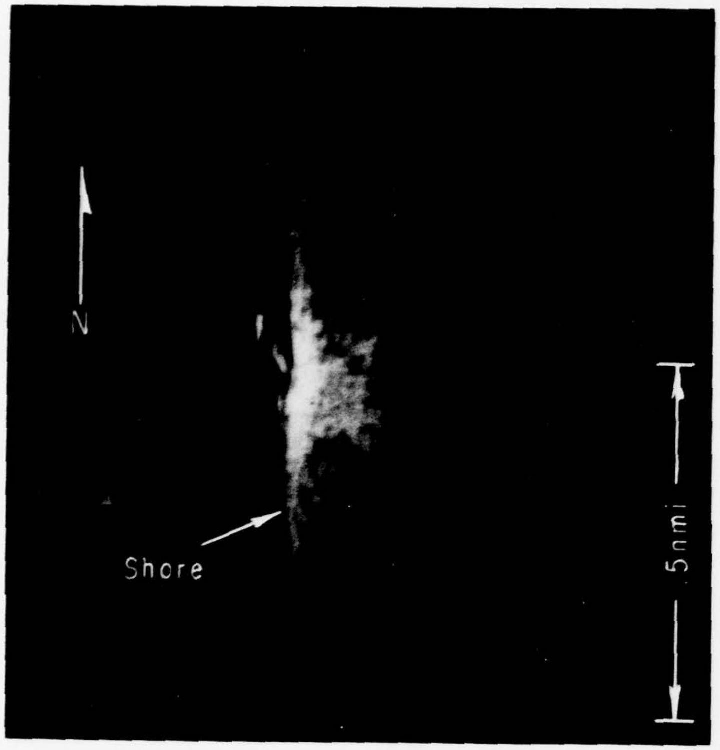

Figure 16. Radar wave image from Cape Cod, Massachusetts, taken at 0026, 12 January 1976. Winds were from the southeast at 30 miles per hour and had been blowing for 3 hours; wavelength measured 53 meters (174 feet) at 926 meters (0.5 nautical mile) from the radar.

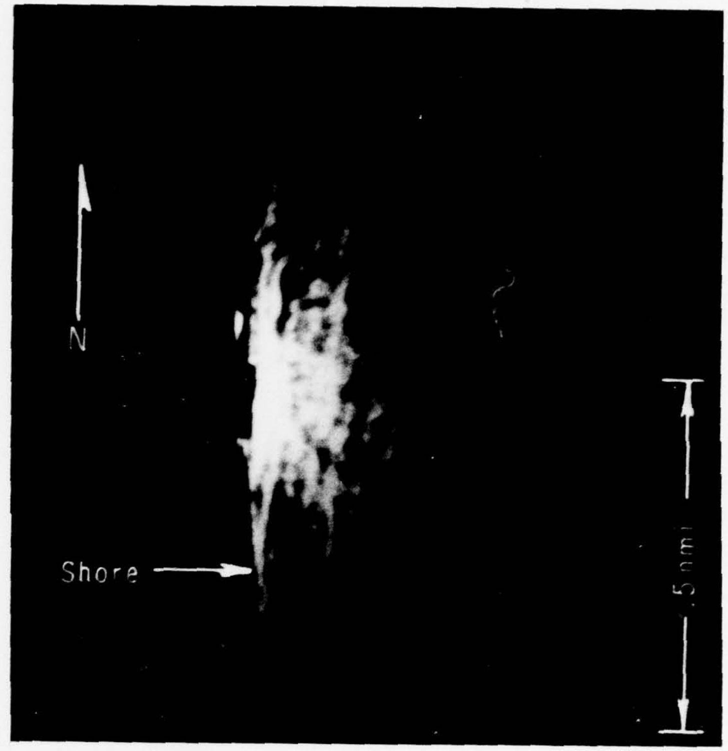

Figure 17. Radar wave image from Cape Cod, Massachusetts, taken at 0500, 12 January 1976. Winds were from the southeast at 28 miles per hour. Wavelength measured 79 meters (259 feet) at 926 meters (0.5 nautical mile) from the radar.

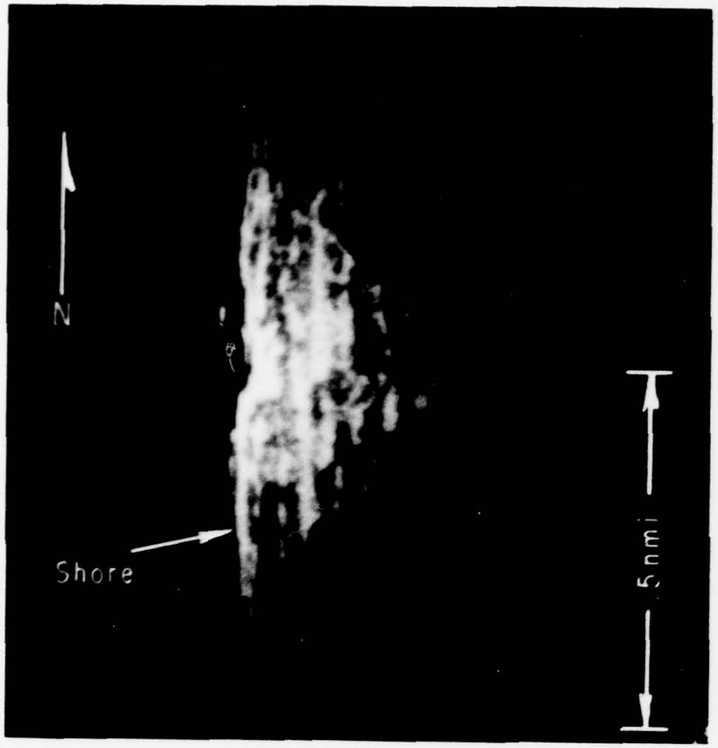

Figure 18. Radar wave image from Cape Cod, Massachusetts, taken at 0924, 12 January 1976. Winds were from the southeast at 35 miles per hour. Wavelength measured 84 meters (276 feet) at 926 meters (0.5 nautical mile) from radar. (Note increase of wavelength and change of wave direction from image in Fig. 16.)

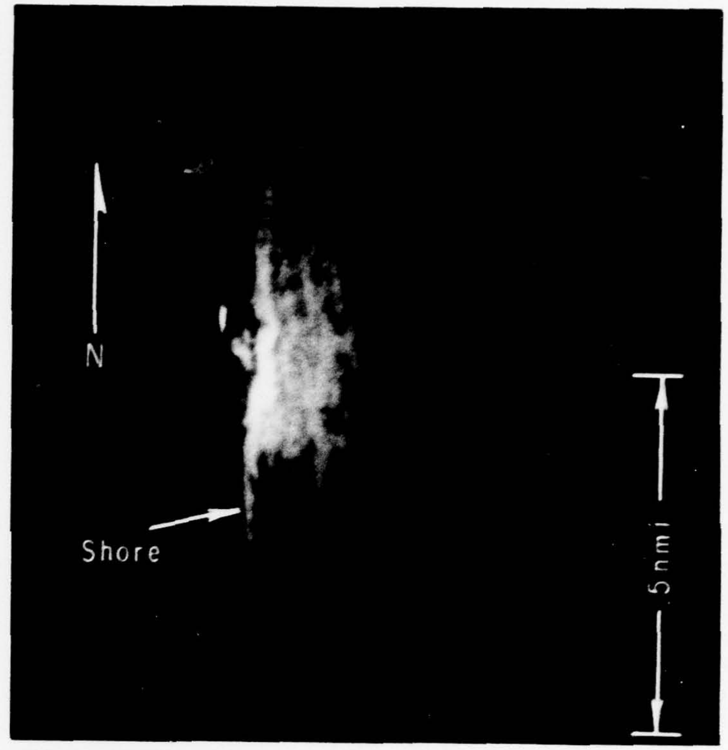

Figure 19. Radar wave image from Cape Cod, Massachusetts, taken at 1342, 12 January 1976. Winds were from the northeast at 35 miles per hour. Wavelength measured 88 meters (289 feet) at 926 meters (0.5 nautical mile) from radar.

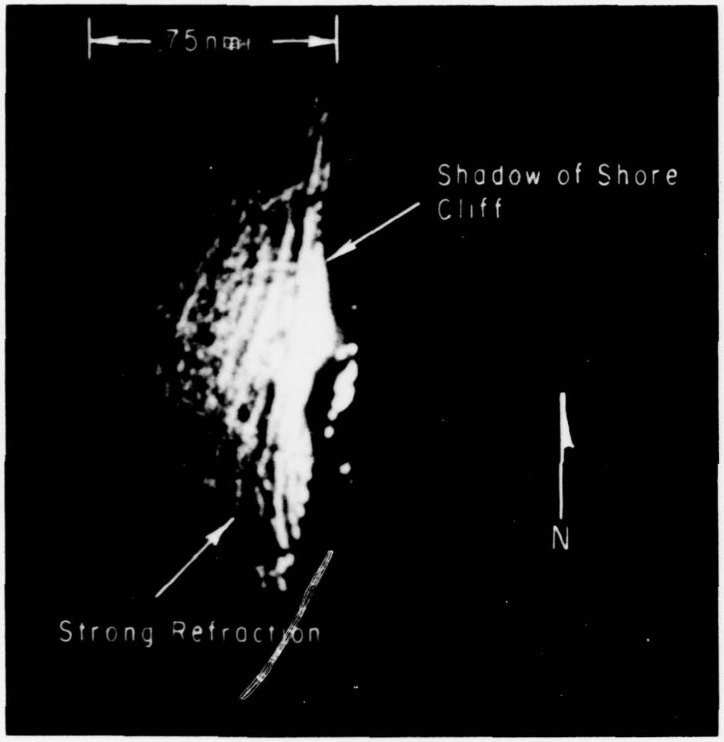

Figure 20. Radar wave image of Torrey Pines, San Diego, California, taken 2 March 1977. Note strong refraction of waves in lower left of image.

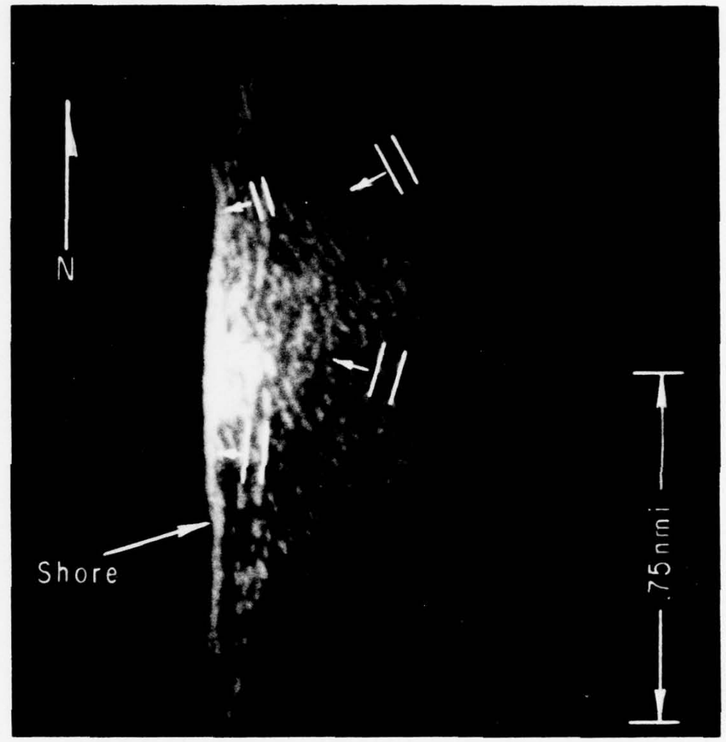

Figure 21. Radar wave image from Cape Cod, Massachusetts, taken 8 January 1976. Note two wave trains approaching the shore from an angle.

Nearshore currents might be measured by tracking float-mounted corner reflectors on a sequence of radar images.

3. Methods for Analysis of Radar Photos.

Because the CERC radar system was designed primarily for obtaining wave direction statistics, a method of analysis is needed to permit rapid and accurate interpretation of the direction of wave propagation from a large set of radar photos. An additional complication is that a single radar picture often shows several wave trains, each of which has a direction and a wavelength to be determined. An effective and convenient method of analysis is to scan the film with a device similar to that shown in Figure 22. The operator can control a 16-millimeter projector while viewing the images, in cinema mode or individually, on a rear projection screen. A rule with a crossbar assembly that fits over the screen can be lined perpendicular to the direction of wave propagation in an area of the image to read the relative angle from a protractor. A true direction can be derived by referencing a known azimuth available from charts. The shore direction or some landmarks shown in the radar photo can be used to define a true azimuth. Any 180° ambiguities can be resolved by observing two successive frames to note the direction the wave crests are propagating. The distance between wave crests can be measured with the rule. Figure 23 shows a radar image with annotated directions and wavelengths. The measurement of the wave direction relative to the shore is shown for two wave trains, where θ_1 and θ_2 are the angles between the wave train propagation direction and the shoreline. The measurement of the wavelength for each wave train λ_1 and λ_2 is also shown.

4. Measurement Errors.

A measurement of the propagation directions for the principal wave trains in the CERC system can be obtained with an accuracy on the order of 8°. Uncertainties in the direction measurement are due to (a) radar angular resolution of about 1°, (b) resolution on the protractor of 0.5°, (c) errors in lining up the ruler perpendicular to the wave crests and in determining a reference angle (estimated to total 5°), and (d) motion of the waves during the time the radar sweeps the sea surface (an error of 1° to 2°).

Errors in measuring wavelength due to resolution of the rule would be least significant in measurements at shorter ranges, such as the 1.39-kilometer (0.75 nautical mile) range. Errors of from 5 to 10 percent in measuring wavelength are encountered at this range.

IV. THEORY OF RADAR IMAGING

Objects are detected with radar by illuminating the scene with short bursts of electromagnetic energy of a discrete frequency. A part of the radiated energy may be returned to the transmitting antenna by specular reflection (mirrorlike reflection) or by back-scattering (discussed later

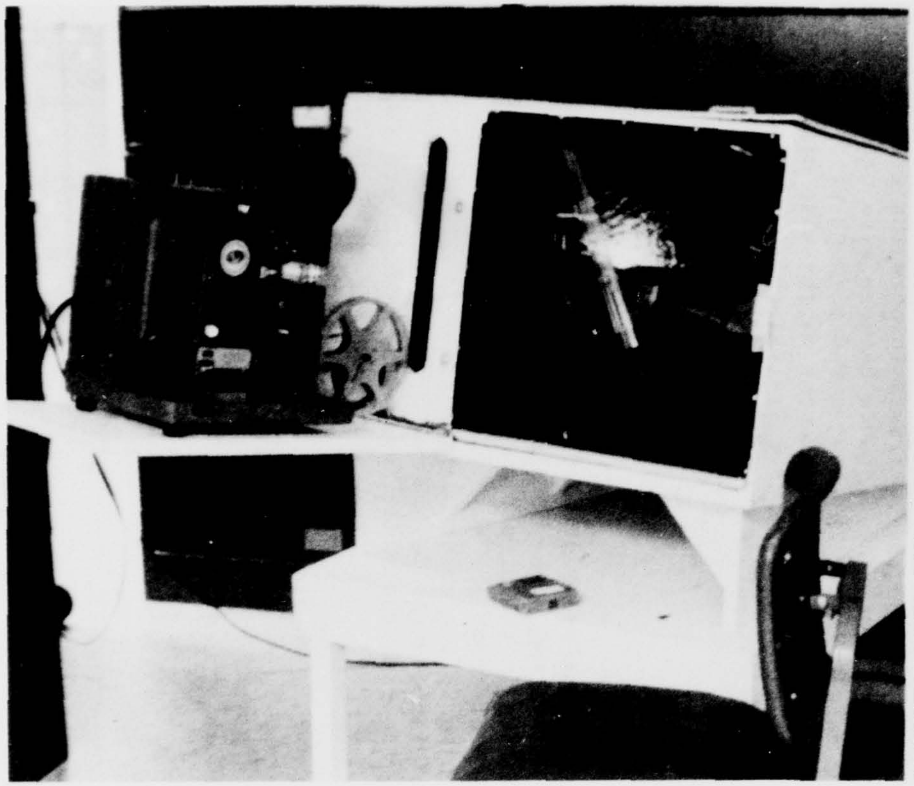

Figure 22. Radar film analysis device.

Figure 23. Radar image from Channel Islands Harbor, California, showing measurement of wave direction and length.

in this section). The distance to the object is determined by the time between the emission of an energy pulse and its return to the transmitter. The direction of the object is determined by varying the orientation of a narrow beam antenna. Images are constructed by scanning the scene and displaying the results on the PPI scope. The sweep of the PPI is synchronized with the antenna rotation so that a return received by the antenna is recorded on the PPI at the appropriate azimuth. The object is imaged as an illuminated spot on the PPI at a distance from the center of the PPI, proportional to the distance of the object from the radar. In the CERC system, the antenna rotates at constant speed around a vertical axis. Thus, the site of the antenna appears near the center of the PPI scope.

1. Radar Resolution.

The resolution of the radar along a radial line is determined by the pulse length. For an object to be detected, a pulse of energy must go out to the object and return to the transmitter; i.e., to detect an object at a distance r, the radiation must cover a distance of $2r$. Thus, the distance is obtained as

$$r = \left(\frac{1}{2}\right) ct \tag{1}$$

where c is the speed of electromagnetic radiation, and t the time interval between the emission of an energy pulse and the return of the same pulse. The pulse, however, has finite duration, τ. Equation (1) should then be written

$$r + \delta r = \left(\frac{1}{2}\right) c(t + \tau) \tag{2}$$

where δr is the uncertainty in measuring r, or the resolution of the radar system in a radial direction The nominal resolution is shown to be

$$\delta r = \frac{c\tau}{2} . \tag{3}$$

Resolution in a radial direction is improved by using small values of τ. Reducing the pulse length also reduces the power of the returned signal, and extremely short pulses may also be associated with a reduction in the reliability of electronic components. A pulse length of 50 nanoseconds (50×10^{-9} seconds) used in the CERC radar system for imaging waves is the shortest pulse width available in commercial marine radars. This type of radar is used in the automatic wave direction system because of its reliability and lower cost. Some special purpose and research radars use shorter pulses which may eventually be used in marine radars. The CERC system has a nominal resolution of

$$\delta r = \left(\frac{1}{2}\right) 3 \times 10^{8} \text{ meters per second} \times 50 \times 10^{-9} \text{ seconds}$$

$$\delta r = 7.5 \text{ meters.}$$

Directional resolution is determined by the ratio of the effective aperture of the antenna (a measure of the effective length presented by the antenna to the incident wave) to the wavelength of the radar waves. The CERC system has a nominal horizontal angular resolution of about 0.9° or 0.0157 radians. Equipment now available (after the CERC system was purchased) will permit an improvement to 0.6°.

The resolution normal to the radius is given by

$$\delta c = r\delta\theta$$

$$= 0.0157r \ . \qquad (4)$$

Thus, the nominal resolution along a radial line and normal to it is equal at a range of 477 meters (1,565 feet). The angular resolution is inferior to the radial resolution at greater distances.

The angular resolution in a vertical direction (23° for the CERC system) is not critical, and little effort has been expended in optimizing this.

The radar in the CERC wave imaging system transmits 3,600 pulses per second with a pulse length of 50 nanoseconds. Since the antenna rotates at 33 revolutions per minute, about 18 pulses are emitted for each 1° rotation of the antenna. Near the center of the scope, at least, the smallest element of the phosphor will sustain an angle of more than 1°. Thus, each spot will display an average of many radial scans. The theoretical optimum radial resolution is also degraded due to distortions of the pulse on scattering and slight misadjustments to radar circuitry. When all factors are considered, the manufacturer claims a resolution of 10 to 20 meters in the radial direction and 0.9° in an azimuthal direction. Therefore, the shortest wave likely to be detected with the system in deep water can be expected to have a period of 3.6 seconds. The shortest detectable periods in shallow water will be even longer.

Radars which use pulse lengths much longer than 50 nanoseconds and angular resolutions of less than 0.9° are unlikely to be satisfactory for imaging the wave field.

2. Scattering Mechanisms.

Radar is scattered from the ocean by two mechanisms. The first is *specular reflection*, where the microwave radiation is reflected by a facet or a surface that is perpendicular to the radar beam. Radar altimeters and other radars that look straight down at the sea obtain return signals via this mechanism. A return can be seen when viewing the surf zone with a radar at grazing angles; facets caused by the breaking waves present surfaces that are perpendicular to the radar beam. Waves

outside the surf zone can also be viewed with the antenna at grazing angles; a second mechanism, *Bragg scattering*, is responsible for the return. In Bragg scattering the ocean waves appear to the microwave radiation as a scattering lattice. Scattered radiation from successive ocean wave crests will reinforce constructively at the radar antenna, if the difference in the path lengths from the radar to each of two wave crests is an integral number of radar wavelengths. Figure 24 illustrates

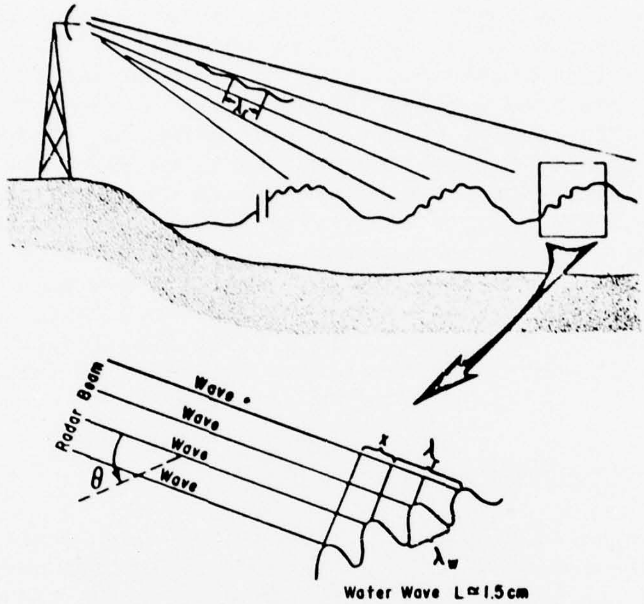

Figure 24. Schematic showing Bragg scattering. Wavelength of radar is λ_r, wavelength of waves is λ_w, and degression angle is θ.

this constructive interference in Bragg scattering where the antenna to scatterer distance is large compared to λ_w, the ocean wavelength. Let λ_r be the radar wavelength and θ the grazing angle which is small. The difference in the round-trip distance between a signal return from the first crest and that from the second crest is $2x$. The condition for constructive reinforcement is then

$$n\lambda_r = 2x$$

$$n = \text{integer (positive and nonzero)} . \quad (5)$$

But

$$x = \lambda_w \cos\theta ; \quad (6)$$

thus, the Bragg relationship is

$$n\lambda_r = 2\lambda_w \cos\theta . \quad (7)$$

The strongest return is usually for the first-order Bragg scattering when n equals 1. For most shore-based or ship radars, the grazing

angle is small and the first-order Bragg scattering is due to ocean waves with lengths on the order of one-half the radar wavelength. For X-band radar, which has a λ_R of about 3 centimeters, the Bragg scattering is from the capillary and short gravity ocean waves.

3. Role of Wind in Scattering.

At times no waves appear on the radar images, although waves are known to be present because they can be observed in the surf zone due to radar return from facets and spray as specular reflection. A case where no waves are seen outside the surf zone is shown in Figure 25. The figure clearly shows a wide surf zone which was caused by swells from two directions. Outside the surf zone, no waves are visible in Figure 25, because since the winds were calm or low, little capillary wave development was present to provide back-scatter radar return. Figure 26 shows the same image taken about 2 hours after Figure 25 when the winds had freshened. The offshore swell is now clearly visible because of the radar return from the well-developed capillary waves modulated by the swell. In general, field tests have indicated that at least a 5-mile-per-hour wind is necessary for the radar to image waves outside the surf zone.

4. Scattering from Wave Crests.

When an X-band imaging radar is used at a shore location, a return is seen from the surf zone due to specular reflection and scatter from small droplets and spray facets perpendicular to the radar beam. A return from outside the surf zone is caused by Bragg scattering, where a strong return is obtained from along the ocean wave crests. Several factors contribute to this phenomenon.

The slope of the sea surface is one factor. The strength of the radar return, measured in terms of radar cross section, σ, is a function of the local grazing angle. The radar cross section, σ, is a measure of the ratio of the power density scattered toward the receiver to the power density incident on a target. Figure 27 shows a cross section per unit area $\sigma°$ plotted versus grazing angle ($\sigma°$ is in decibels; i.e., $\sigma°(dB) = 10 \log_{10} \sigma°$). In the figure, the graph for an X-band horizontally polarized signal shows an increase in return with increased grazing angle. Thus, a better return would be expected from the upper part of the forward face of gravity waves, where the local grazing angle between the water surface and a radial line from the radar antenna is largest.

A second factor is that the antenna is mounted at such a low elevation that most wave troughs are shadowed by the previous crests but high enough to ensure that a high wave would not shadow any following wave crests. The optimum antenna elevation would be between 10 to 20 meters (33 to 66 feet). With the antenna below 10 meters, the grazing angle is

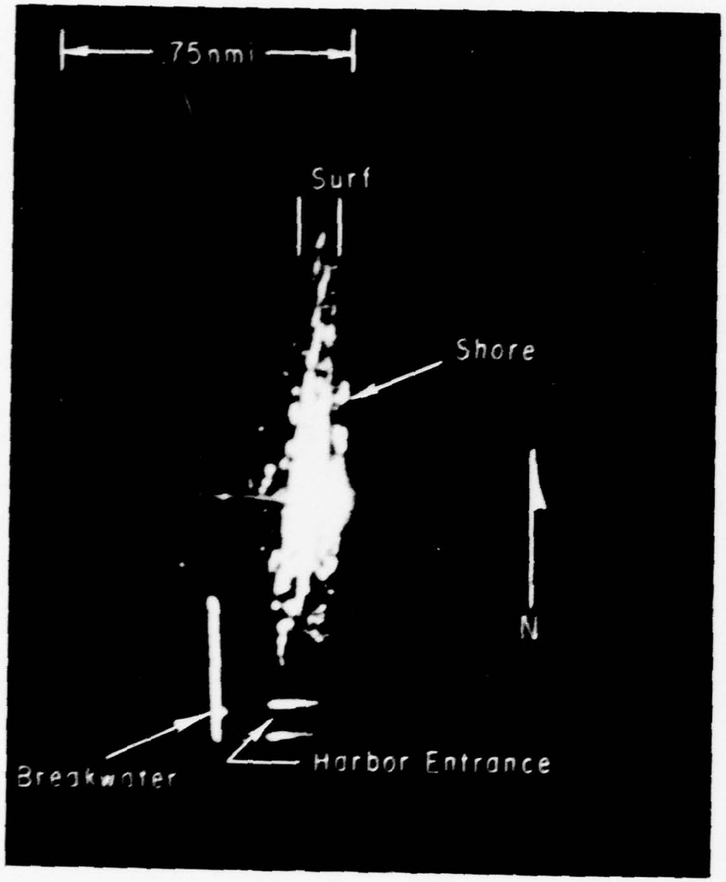

Figure 25. Radar image taken with the CERC radar at Channel Islands Harbor, California. At the time no wind was present, and no waves are seen except in the surf zone.

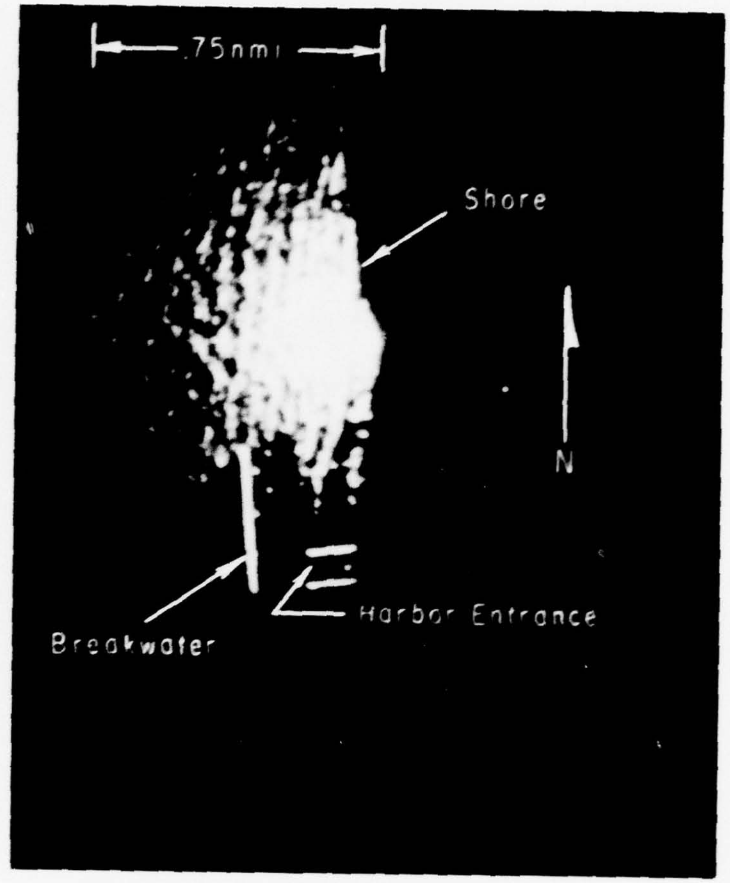

Figure 26. Radar wave image taken at Channel Islands Harbor 2 hours after the photo in Figure 25. Waves are now clearly shown out to the full 1.3 kilometer (0.75 nautical mile) range.

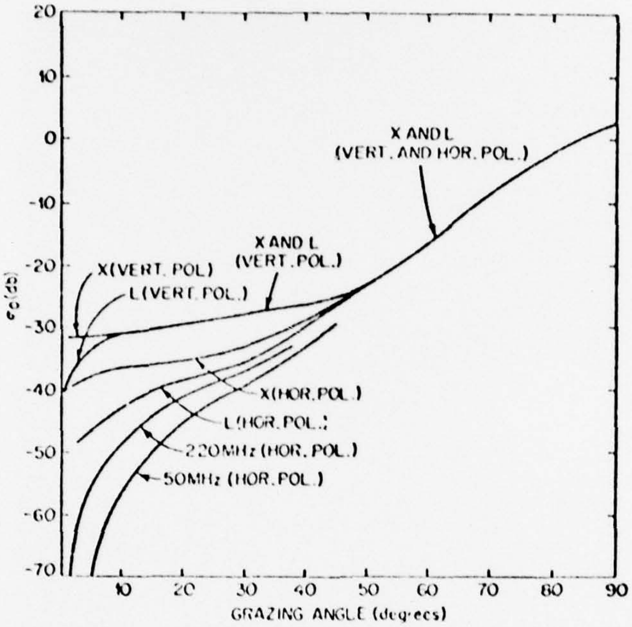

Figure 27. Composite of σ° data for a "medium" sea (Skolnik, 1970).

so small that many waves which are more than 1.5 kilometers (4,920 feet) from the radar, will not be seen because of shadowing by nearer waves (see Fig. 28), and also because of the small radar cross section at small grazing angle. At elevations of about 20 meters, the radar begins to see some return from wave troughs which makes the lines of the wave crests harder to distinguish (Fig. 29).

Another factor is due to the modulation of the radar-scattering capillary waves by the longer gravity waves and swell. This modulation, due to hydrodynamic interactions, results in a concentration of capillary wave energy near the wave crests giving increased capillary amplitude and stronger radar return there. Phillips' (1966) description on the straining of small, short waves by the larger waves is one of the hydrodynamic mechanisms contributing to this concentration. The effect of modulation of capillary waves on radar return has been investigated by Yeshchenko and Lande (1972), Keller and Wright (1975, 1976), Plant, Keller, and Wright (1978), Reece (1978), and Wright (1978).

The rotating display sweep registers an image of the sea scatterers from the wave crests on the PPI display which in turn can be recorded by time-lapse photography. The waves usually exhibit a long-crested character (also appears in aerial photos) and appear as light and dark strips across the PPI scope. It is often assumed that the light areas represent the front face or crest of the waves, and that the dark strips represent the backface or trough. The correctness of this intrepretation is

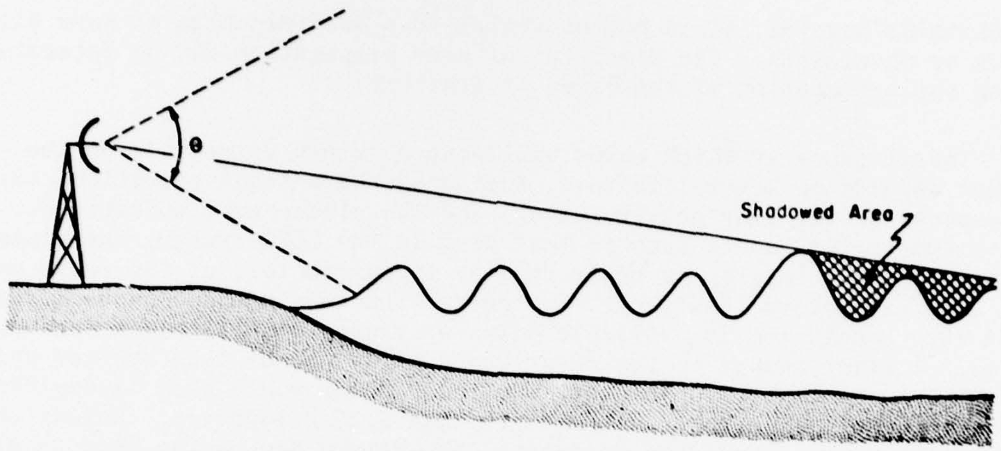

Figure 28. Schematic showing how for low radar antenna elevations larger waves, at times, shadow the following wave crests and limit effective range of instrument for imagery.

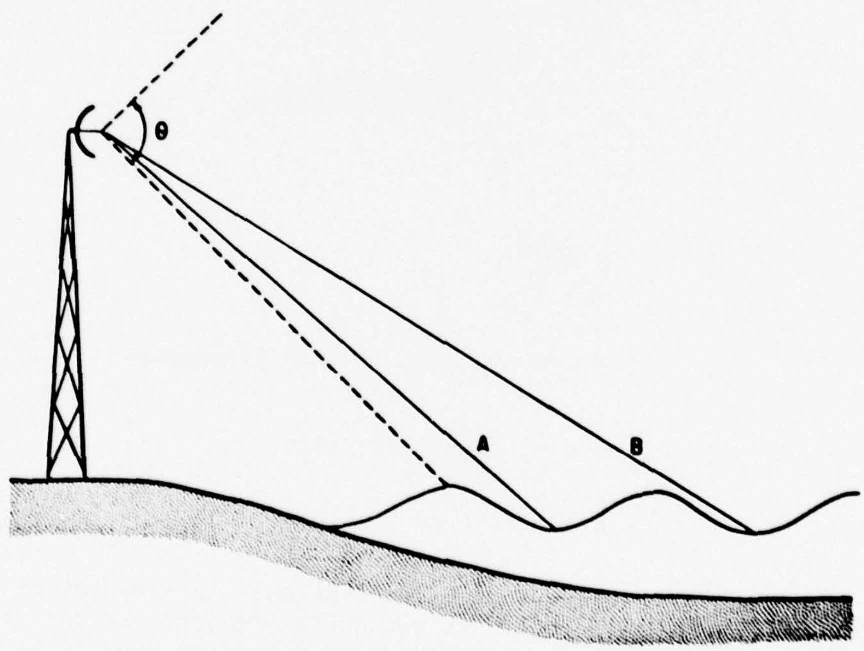

Figure 29. Schematic showing how high radar antenna elevations give a radar return from troughs of waves, decreasing the contrast in the imagery.

uncertain; however, it is not essential to a determination of wave direction or wavelength. The direction of wave propagation can be determined from the orientation of the lines of scatterers.

The distance at which waves will give a return detectable on the radar depends on several factors, including the antenna elevation, the steepness of the long gravity waves, and the atmospheric conditions. With commercial radars such as that used in the CERC system, the maximum range for wave imaging is restricted by the parameters of the radar unit to 5.28 kilometers (3 miles). The pulse width of 50 nanoseconds needed for wave resolution is available only for ranges of 5.28 kilometers or less. A minor change to the radar would allow use of this shorter pulse for the longer ranges. However, the radar power would then become the limiting factor for the ranges longer than 5.28 kilometers. Unless the transmitted power could be increased, the return may be too weak to give wave images.

If radar radiation is assumed to travel in straight lines, then the range would also be expected to be restricted by the curvature of the Earth as shown in Figure 30. If d = 5.28 kilometers, then a minimum radar height, h, is found by

$$(r + h)^2 = r^2 + d^2$$

$$r^2 + 2\,hr + h^2 = r^2 + d^2 \qquad (8)$$

$$h(2r + h) = d^2$$

but

$$r >> h$$

$$h \approx \frac{d^2}{2r}\ , \qquad (9)$$

let

$$r = 4{,}000 \text{ miles } (6{,}439 \text{ kilometers})$$

then

$$h = \left(\frac{9}{8{,}000}\right) 5{,}280 \text{ feet}$$

$$h \approx 6 \text{ feet } (1.8 \text{ meters})\ .$$

Since radar waves follow a straight line only in a medium of constant index of refraction, this method is not quite correct. In the atmosphere, the gradients of humidity and density cause the radar beam to bend. Typically in a standard atmosphere, radar radiation starting out parallel to the Earth will travel along an arc with a radius approximately equal to 4/3 the radius of the Earth. The actual radius varies with the vertical gradient of temperature and humidity in the atmosphere. The radius is least when temperature increases and humidity decreases rapidly with

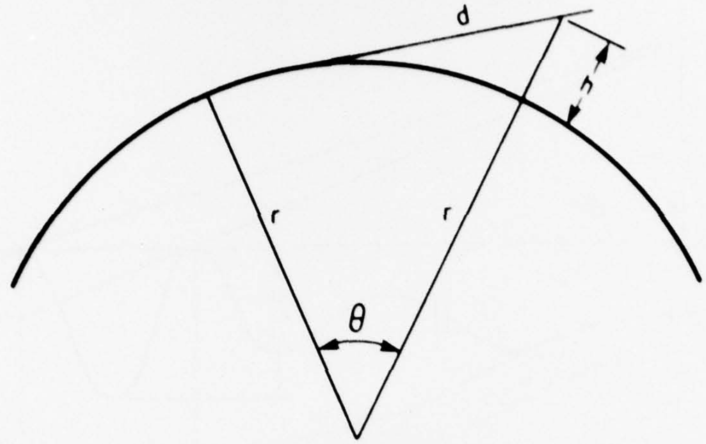

Figure 30. Schematic showing the restriction on line-of-sight by curvature of the Earth. h = height of radar, r = Earth's radius, and d = range by line-of-sight.

increasing height. The distance to the horizon for a radar experiencing this refraction can be given as (Skolnik, 1962, pp. 506-509):

$$d = \sqrt{2kah} \qquad (10)$$

where a is the radius of the Earth. The term Ka is then an effective radius of the Earth. For k = 4/3, equation (10) can be conveniently written where d is measured in statute miles and h in feet as

$$d(\text{statute miles}) = \sqrt{2h(\text{feet})} \qquad (11)$$

or

$$h(\text{feet}) = \frac{(d[\text{statute miles}])^2}{2}$$

where d is the distance to the horizon, and h the height of the radar; for d = 5.28 kilometers (3 miles), then h = 1.4 meters (4.5 feet).

For most radar installations, this antenna elevation is easily obtained. However, further restrictions on the useful distance that radar can view waves are imposed because the radar scatterers ride on the forward face of the longer gravity waves. Thus, with an antenna at the minimum required height as determined above, waves would not be seen out to 5.28 kilometers because of shadowing of the radar scatterers by nearby gravity waves. An example of the radar antenna at an elevation of 4.6 meters (15 feet) is shown in Figure 31 where two waves only 1.6 kilometers (1 mile) from the radar with 1.5 meters (5 feet) in height are inspected. Geometry shows that only the top 23 centimeters (0.75 foot) of the second wave is seen by the radar. Unless strong winds were present, the return from this small area of the wave would likely give a weak radar return. Return from following waves farther from the radar would give an even weaker return; therefore, the effective range for this installation is about 1.6 kilometers.

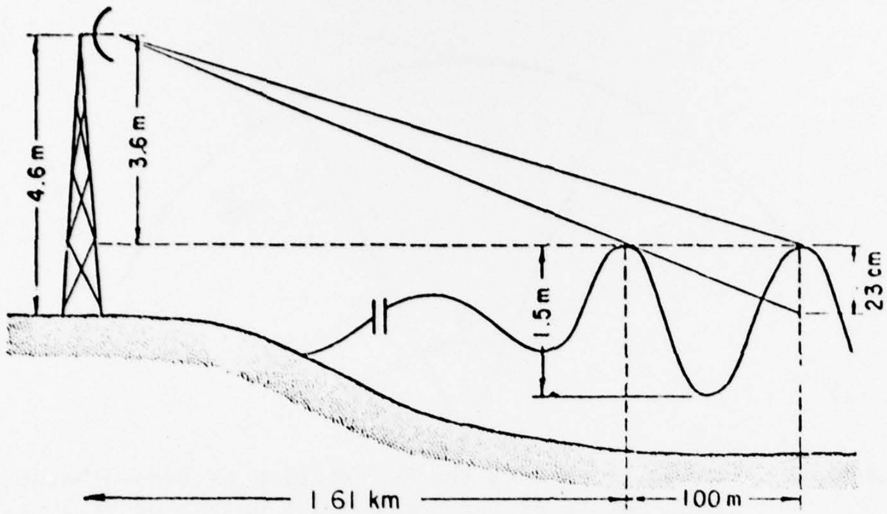

Figure 31. Schematic showing the illumination of wave crests by radar at 4.6 meters elevation.

Several other complicating factors make exact calculations of maximum range difficult in every situation. These include the decrease of radar cross section with incidence angle (see Fig. 26), the unknown phase of the radar scatters with respect to the long waves, variation in temperature and humidity in the air, and the variation in height of the long waves. Thus, the choice of the optimum antenna elevation must be made empirically with consideration of the wave height to be expected, the features to be investigated, and the sites available.

V. VALIDATION

Wave data from imaging radar should be compared with wave data from other devices. At least two types of comparative data may be used:

(a) Other types of wave imagery, including aerial photography and aircraft or satellite radar such as synthetic aperture radar (SAR) and side-looking radar (SLAR).

(b) Data from conventional wave gages or arrays of conventional wave gages.

All imaging processes present a nearly instantaneous, two-dimensional view of the water surface. For aerial photography, the duration of an observation is a few milliseconds; for scanning radar (used in these experiments), successive parts of the image are formed at later times, and the duration of data collection is about 1 to 2 seconds. In all imaging processes, ripples are required on the water surface to reveal the presence of longer waves.

With aerial photography, the principal process for obtaining information about the water surface is specular (mirrorlike) reflection; for surface-based radar, the principal process is Bragg scattering.

Most wave gages record the time history of some property of the wave at a fixed point, or a very small area, over a finite time interval, usually about 20 to 30 minutes. When an array of gages is used to determine wave direction, it is necessary to postulate an analytic function which describes the geometry of the sea surface and to determine the coefficients in this function from gage measurements.

Measurements from a single gage generally represent some type of time average. When arrays are used, space-averaging based on discrete points is also involved.

Both types of data yield information on waves, but the information revealed by different procedures is not identical because each observation technique concentrates on one or two facets of wave behavior and neglects others. Exact agreement is not to be expected. Nevertheless, the comparisons discussed in this section reveal a significant level of agreement.

The primary source of comparison data was the West Coast Experiment (sponsored by National Aeronautics and Space Administration (NASA)) conducted during February and March 1977 off the coast of southern California (Shemdin, Inman, and Blue (1977)). The objective of the CERC participation in this experiment was to conduct a field shakedown test of the first prototype CERC radar system, which had only recently been assembled, and to validate as many CERC radar measurements as practical. Certain factors prevented the CERC system from performing in an optimum manner. The limited time for deployment and the available locations for operation did not allow ideal antenna elevations. A subsequent discovery indicated that the radar was not properly tuned and that misadjustment of pulse width may have given a pulse as wide as 150 nanoseconds, three times the desired value. This would have resulted in the radial resolution being degraded from about 10 meters to between 30 or 40 meters (98 or 131 feet). However, radar wave images were produced which provided wave direction measurements to compare with measurements from other instruments operating simultaneously. These comparisons along with some information gathered during an earlier experiment at Cape Cod are discussed below.

1. Comparison with Aerial Photos.

During the West Coast Experiment in March 1977, several U-2 aerial photo missions were flown off the California coast in the area of San Diego. Simultaneously, radar images of the waves were obtained with the CERC radar system located at Mission Beach, San Diego. Two cases exist where photos (as shown in Fig. 2) could be compared with radar images. In these cases, measurements were made of the directions of propagation for long-crested wave trains detectable on the radar image and the U-2 photos. Figure 2 shows a part of the aerial photo taken 29 March; Figure 32 shows a photo taken 14 March. The results are shown in a Table. The CERC radar images and the U-2 photos were both taken within a 10-minute period on each of the two dates. Wave measurements on the imagery were made either at the U.S. Navy Undersea Center (NUC) tower at a depth of

Figure 32. Aerial photo taken by NASA U-2 aircraft over Mission Beach, San Diego, California, 14 March 1977.

Table. Comparison of information from CERC radar images with that obtained with other direction measuring devices.

Date (1977)	Time	Wave direction at NUC[1]	Wavelength (m)	Wave period (s)	Wave direction	Wavelength (m)	Wave period (s)	Wave direction	Direction refracted to NUC	Wavelength (m)	Wave period (s)
		CERC radar			U-2 aerial photo			SAR[2]			
14 Mar.	1130	283° ± 4°	84 ± 11	8.6 ± 0.9	284° ± 2°	80 ± 16	7.6 ± 0.9				
		261° ± 4°	168 ± 22	15.5 ± 2.0	264° ± 3°	120 ± 16	10.2 ± 1.0				
					316° ± 2°	40 ± 16	5.1 ± 0.5				
29 Mar.	1100	282° ± 4°	107 ± 21	9.2 ± 1.4	288° ± 2°	89 ± 16	8.1 ± 0.9				
		256° ± 4°	160 ± 22	14.7 ± 2.2	257° ± 3°	109 ± 16	9.4 ± 1.0				
					320° ± 2°	30 ± 16	4.4 ± 1.0				
28 Mar.	1800	285° ± 4°	136 ± 22	10.8 ± 1.5				286°	283°	138	9.4 ± 0.1
		261° ± 4°	105 ± 22	9.9 ± 1.4				259°	262°	208	11.5 ± 0.2
		242° ± 4°	182 ± 22	15.2 ± 1.5							

[1] U.S. Navy Undersea Center.

[2] Synthetic aperture radar.

Note: Wave period estimates were obtained from wavelength and depth through Airy wave theory; wavelength measurements were not all made at the same depth.

18.3 meters (60 feet) or shoreward of the tower with wave direction calculated at NUC by refraction theory (McClenan, 1975). The measurements were made manually with a protractor and straight edge. The true bearing of 275° from the NUC tower to the radar site was used as a reference. To resolve the 180° ambiguity, several radar images were viewed which showed that the waves were moving shoreward. For the U-2 photos, it was assumed that the waves were propagating toward the shore.

In both cases, two wave trains were detected on the radar images, and the directions for these wave trains agreed well with measurements from the U-2 photos. However, in both cases, another very short wave train appeared in the U-2 photo but was not detected by the radar. Perhaps this was due to the misadjustment of the pulse width resulting in a radar resolution that was too poor to image the short wave train. With the radar optimally adjusted, it is expected to produce images of waves with lengths on the order of 20 meters. Wave trains with lengths of 35 meters (115 feet) have been measured by a radar with the same design resolution as the CERC radar; these results are discussed later in comparing pressure gage data with radar measurements at Cape Cod.

Wave images were also collected by JPL during the West Coast Experiment using a SAR mounted in the NASA Convair 990 aircraft. On 28 March, a SAR image of the waves was taken in the Mission Beach area at the same time CERC radar images were obtained (see Fig. 33). Figure 34 is a two-dimensional Fourier transform of the marked area of the SAR image. On the transform, the predominant wave train shows as a bright radial band. A close examination also shows a faint second band oriented 28° in a counterclockwise direction from the predominant band, which corresponds to a second wave train. These light lines or bands in the transform are normal to wave crests. Wave direction and period for the SAR data were taken from direction plots derived from the Fourier transform and supplied by JPL. The CERC radar results for 1800 on 28 March are based on an average of three images taken within ±30 minutes of 1800 (photo of the radar scope for this observation is shown in Fig. 35). The 285° wave train appears on all three images. Each of the 261° and 242° trains appears on only two of the three averaged images. The Table shows that when the direction of the prominent wave trains of the SAR image are refracted to the NUC tower (location of the CERC radar measurements), there is good agreement in the wave direction measured by the two instruments for these wave trains. However, a third train from 242° with a period of 15 seconds appears on the CERC radar and not on the SAR. A possible explanation is that three wave trains were present—the prominent train from 285°, a second from 263°, and a third swell train from 242°. Such a swell, even if the wave height were low, could show up on the CERC radar because of shadowing of wave troughs with the low antenna elevation. It might not have appeared with the SAR because of the small amount of modulation of the radar-scattering capillary waves resulting from such a wave train's small wave steepness.

The Table shows that for 14 and 29 March the wave periods for the long-wave trains measured from the CERC radar image do not agree well

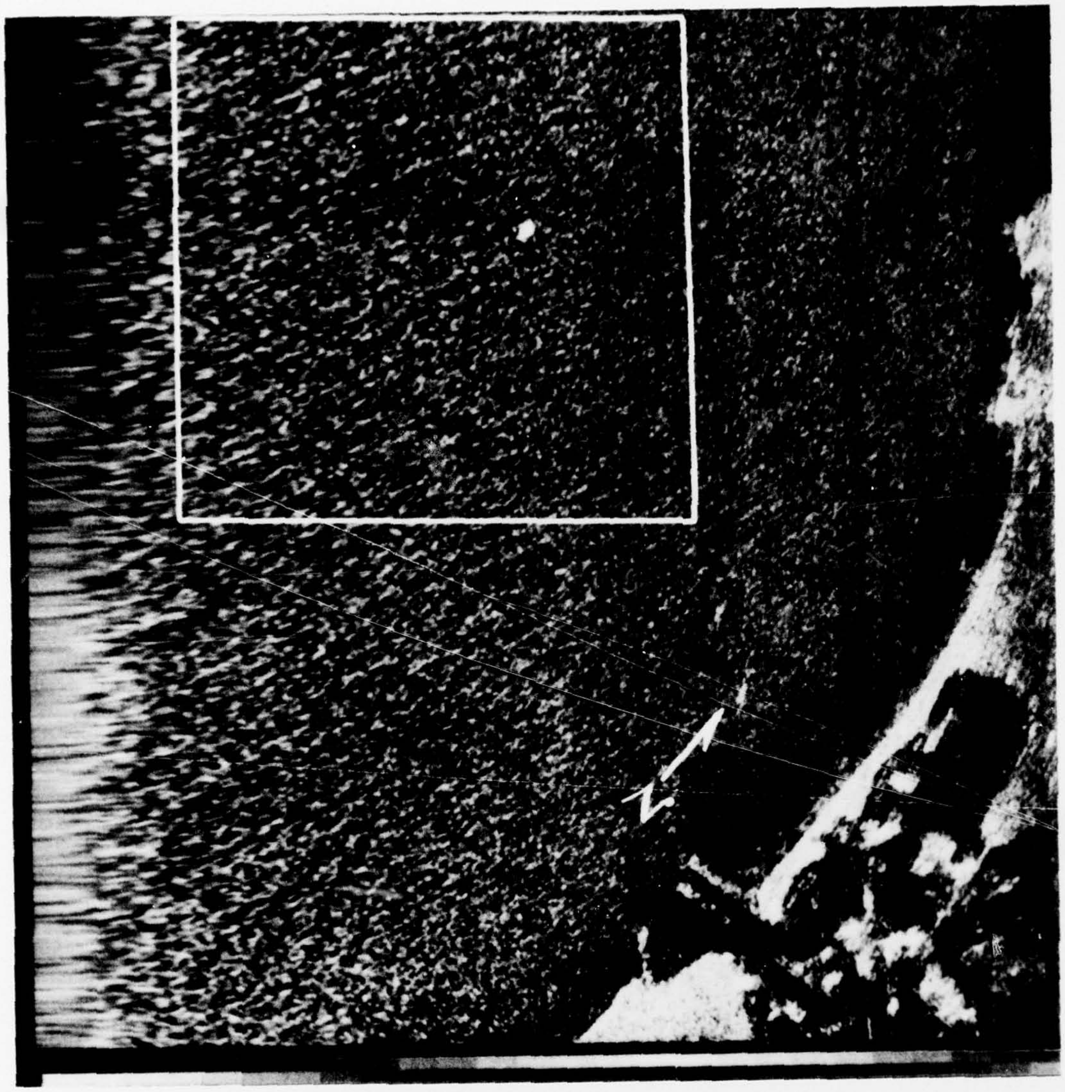

Figure 33. SAR image of Mission Beach at San Diego, California, 28 March 1977. Outline shows approximate area used for transform in Figure 34.

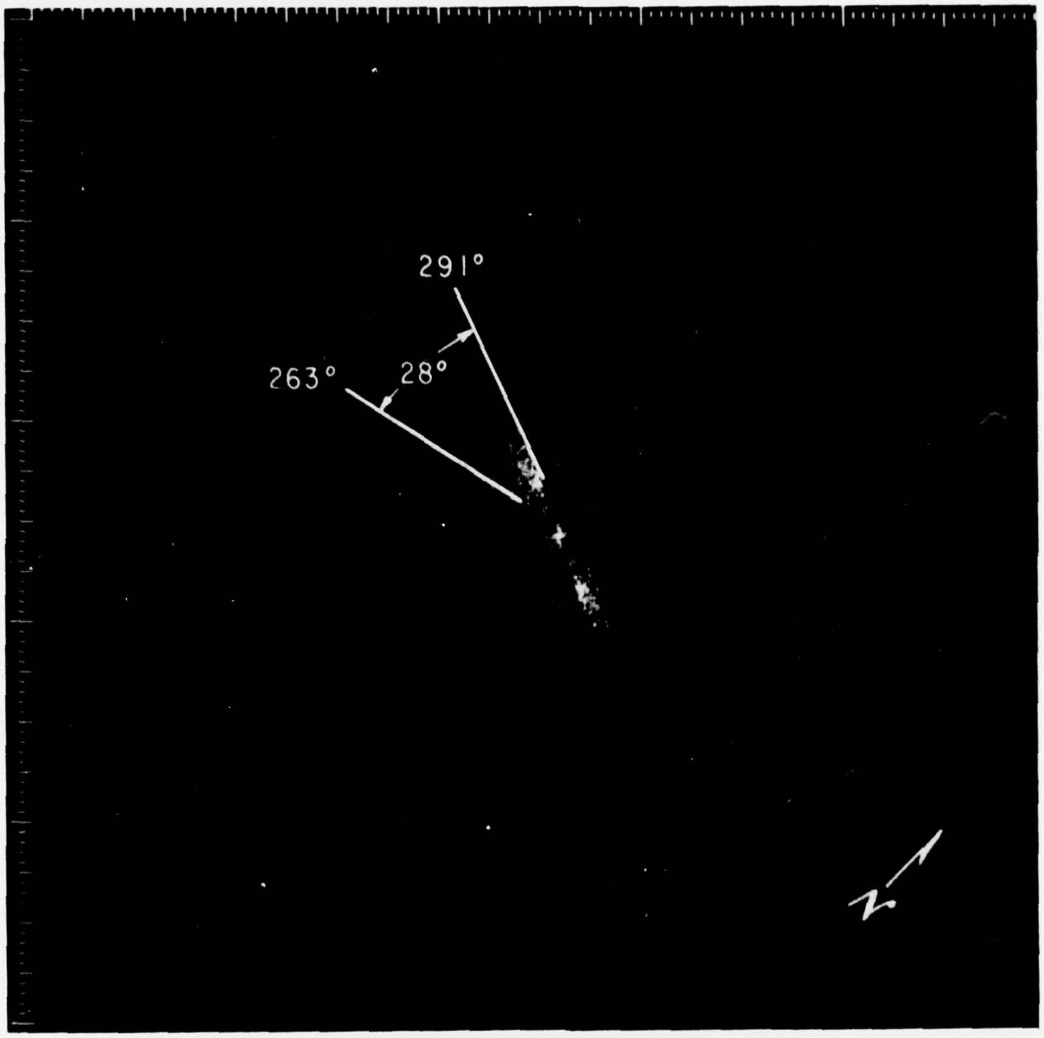

Figure 34. Two-dimensional Fourier transform of SAR image shown in Figure 33.

Figure 35. CERC radar image at Mission Beach, 28 March 1977.

with the periods measured from the U-2 photos. These long waves were part of secondary wave trains which did not show up well on either the aerial photos or the radar images. Thus, the wavelengths were difficult to determine with the manual analysis scheme used. In general, a Fourier transform of the photos should provide a more reliable wave period measurement. A reliable wave period measurement from the radar images may be obtained by recording the time for one wavelength to pass a fixed point.

2. Comparison with One-Dimensional Wave Spectra.

One-dimensional wave spectra from a pressure gage have also been used in radar imagery evaluation. The Decca marine radar, with specifications similar to the CERC radar, was operated for 2 weeks at Cape Cod. Wave images were obtained with the radar operating at 18 meters (60 feet) above mean sea level (MSL). Simultaneously, a pressure gage was operated offshore of the radar location. The lengths of the visible wave trains were measured on the radar photos at the same location as the bottom-mounted pressure gage. From the spectrum obtained with the pressure gage, a peak period was determined from which wavelength was calculated using linear theory and depth. A scatter plot (Fig. 36) of radar-measured wavelength versus that from the pressure gage shows a good correlation. The radar-measured wavelengths are systematically shorter

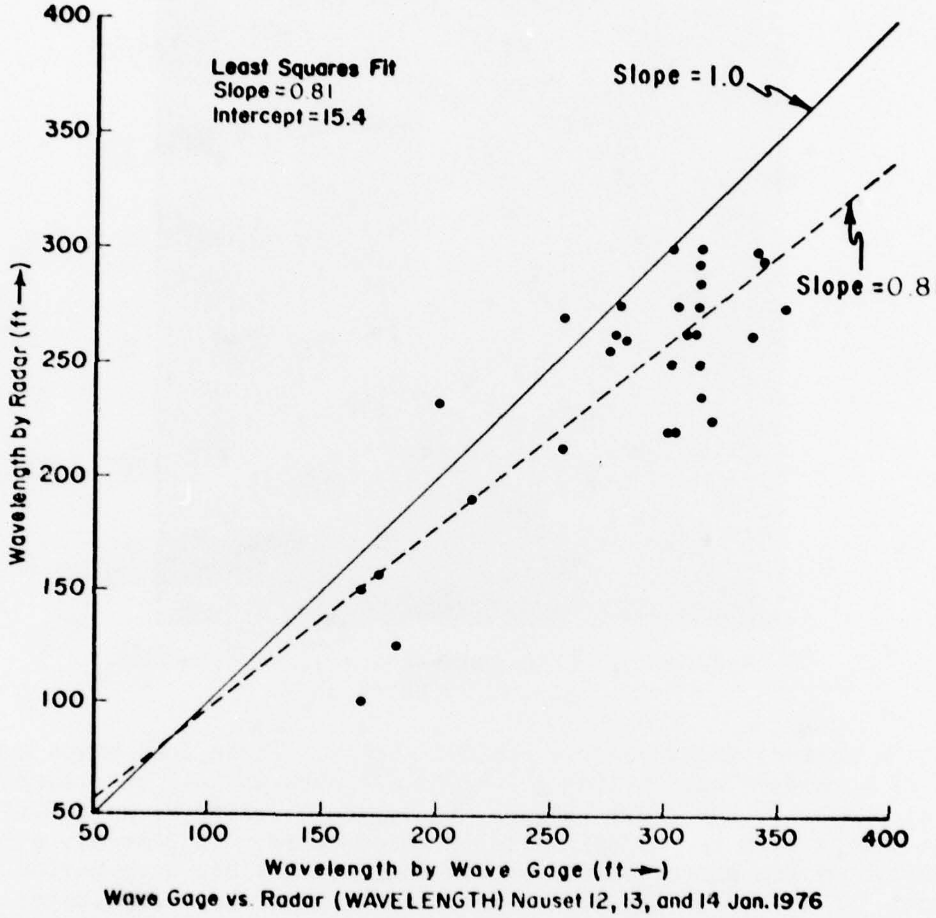

Figure 36. Scatter plot of radar measurements versus pressure gage measurements of wavelength.

than those seen by the pressure gage. The precise position of the pressure gage was not known. The error could be accounted for if the wavelength measurements were made on the radar image at a location shoreward of the actual pressure gage position. This hypothesis is supported by a scatter plot (Fig. 37) of the wave period measured by the pressure gage and the wave period obtained using the wavelength as measured by CERC radar, the depth from charts, and Airy theory. This is the same data set used in Figure 36, but for period no systematic error is seen.

An extensive comparison study of wave direction as determined by the CERC radar, aerial photos, SAR imagery, and a pressure gage array is presented in Mattie, Evans, and Hsiao (in preparation, 1979).

VI. OTHER RADAR DEVICES AND DIRECTION MEASURING SYSTEMS

1. Radar Devices.

Radar is used in many different ways to obtain information on ocean waves and winds. Radar altimeters used on aircraft and satellites can provide information about wave height (Rufenach and Alpers, 1978). These satellite altimeters measure significant wave height to an accuracy of 1 meter (3.28 feet) or 25 percent of the actual height over a range of 1 to 20 meters. Images of an ocean surface area can be obtained from aircraft and satellites by the SAR (Elachi, 1978). In the SAR system, the return along the flight path is combined in the data processing so that the angular resolution is greatly improved, and an antenna is simulated that is much longer than the one actually carried on the platform. With this increased angular resolution, the satellite SAR's have a resolution cell 25 by 25 meters (82 by 82 feet). Spatial wave and current information can also be obtained with high frequency (HF) radar. A typical radar of this type has a wavelength of 5 to 100 meters (16.4 to 328 feet), and usually requires an antenna array on the order of one to five wavelengths long to form a fairly narrow azimuthal beam. Barrick (1977) has developed a phase-difference technique to obtain narrow beams with small HF antennas. Most HF units are doppler radars which measure the speed of the radar scatters from the doppler shift of the radar signal. When HF radar is scattered from the sea surface, the first-order doppler return can give a measure of surface currents. Lipa (1978) discusses the theory and verification from one experiment for a method to obtain wave directional spectra from the information contained in the higher order doppler return. The resolution provided by this system is unlikely to be fine enough to meet the needs of coastal engineers for nearshore measurements.

A variety of other specialized radars is available for making specific measurements in the ocean environment; e.g., a radar scatterometer provides estimates of local wind velocities by measurement of the radar cross section, because at some radar wavelengths, the cross section is a function of windspeed. An inexpensive radar with a resolution fine enough to obtain images of sea surface wave fields for ranges to include coastal wave phenomena is needed. The CERC radar will meet this need for many operational conditions.

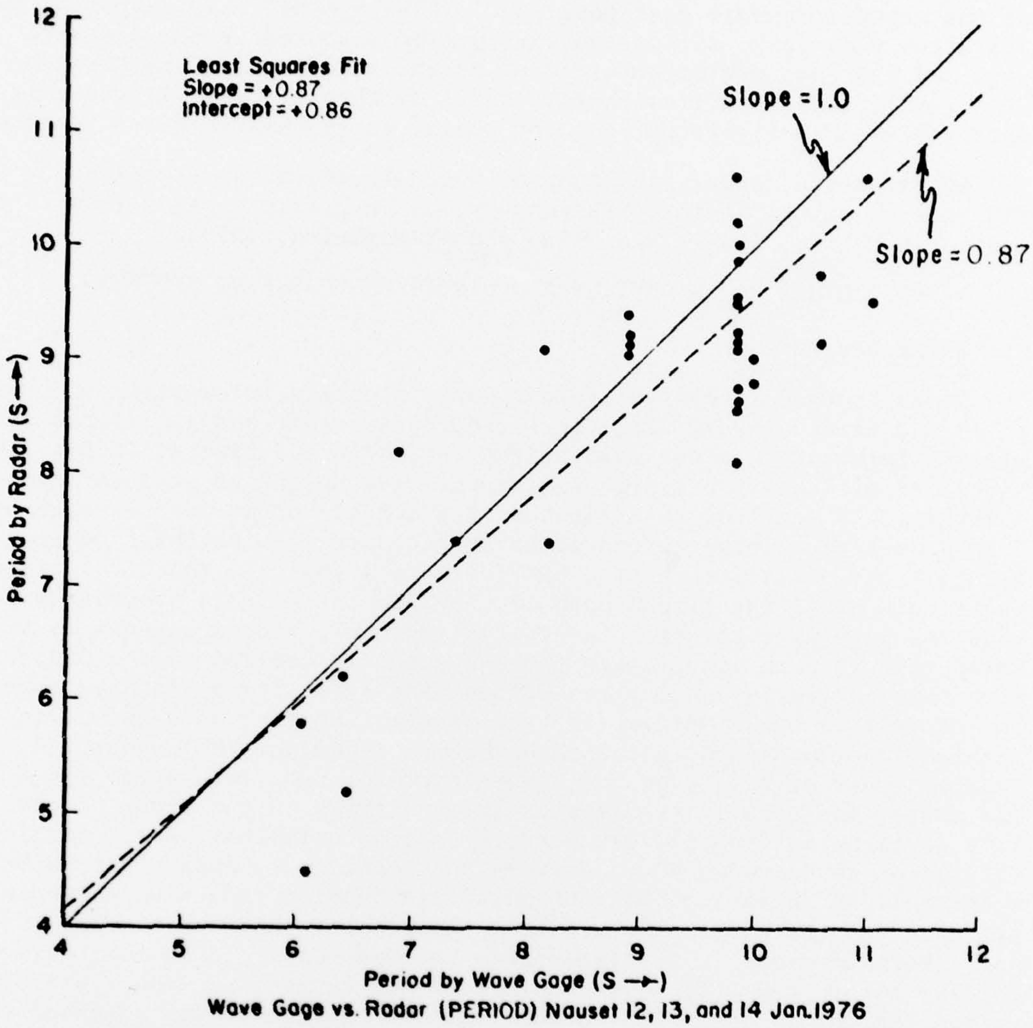

Figure 37. Scatter plot of radar measurements versus pressure gage measurements of period.

2. Determination of Wave Direction from an Array of Sensors.

Information on wave direction is available from analyses of the records obtained from an array of wave sensors. In essence, this procedure is based on an assumption about the geometry of the water surface and the relation between the wave height and the pressure, the velocity or both, as a function of depth. The assumption may have a deterministic or probabilistic form, but it must be expressed in analytic form so that coefficients obtained from the wave record analyses can be used to specify the distribution of wave directions.

The simplest model assumes that the important waves are low, monochromatic, unidirectional, long crested, and are traveling without change of shape over a horizontal bottom. If these conditions hold and the phase differences between three wave gages in a two-dimensional array can be measured, a unique wave direction can be derived from the data. A unique direction may also be determined from measurements of pressure and water particle velocity along orthogonal horizontal axes or from measurements of the wave height and surface slope along these axes.

It may also be assumed that the wave energy at a given frequency is distributed over a range of directions according to a formal law and to use wave observations from an array of sensors to determine the coefficients in the selected law. It is important to note that the determination of wave direction by analyzing the records from an array of sensors is necessarily based on an assumption about the law which governs the distribution of wave directions. If the assumption is precisely correct and there are no instrument or analyses errors, the information on wave direction will be correct. If the basic assumption is incorrect, the results of the analyses may be misleading even when there are no instrumental or data processing errors.

Techniques for determining wave direction by analyzing the records from an array of wave gages have been reported by Fujinawa (1974), Panicker (1971, 1974), Esteva (1977), and others.

When an image of the wave field is analyzed, some trains of low waves may be overlooked; however, if a wave is identified in the image of the wave field, then that wave train must have been present on the ocean and the direction determined from the image cannot be greatly in error.

VII. DISCUSSION

The CERC radar system was designed to automatically obtain images of the wave field for measurement of wave direction and length. The system also has the capability of determining wave speed, current speed and direction, information on refraction, and a potential of obtaining additional information.

1. Additional Capabilities of CERC Radar System.

There are two situations in which the CERC radar system can be used to measure wave period. If the radar is in the manual operation mode,

an operator can leave the radar on a single range and view the return. To measure the period, the operator would either select a stationary radar scatterer, such as a tower or end of a pier shown in the radar photo, or chose a point on the PPI and determine the time (with the aid of the LED clock) for one wave (crest to crest) to pass the chosen point on the scope. For better accuracy, the time is determined for the passing of 10 waves; the wave period would then be this time divided by 10. From a radar picture, the wave period could be found by measuring the wavelength at a location in the frame where the depth is known. Linear wave theory could then be applied to give an estimate of the period.

Information on wave height may be obtainable with the CERC radar. The strength of the radar return is a function of the amplitude of the capillary waves and the local grazing angle. Since the capillary waves are modulated by the longer gravity waves, it would then appear that the modulation of the radar return signal should contain information on the long-wave heights. A complicating factor is that the capillary wave development is influenced by the local winds. A complete theoretical model is not now available to relate radar cross section or radar return signal strength to wave height for radars such as the CERC radar. However, an empirical calibration of the radar return for wave height may be possible.

2. Future Plans.

The main directions for further development are to increase resolution of the radar system and to develop automatic data reduction. The CERC system has a 2.74-meter (9 feet) antenna array; however, a recently available 3.66-meter (12 feet) array will give a slightly better angular resolution of 0.6° instead of 0.9°. More importantly, it will give a better signal-to-noise ratio.

A shorter pulse width to improve resolution and perhaps provide better radar wave images may be possible with only minor adjustments to the radar. One drawback in shortening the pulse width is that this lowers the average power transmitted. Weak scatters imaged when using the 0.05-microsecond pulse, may be invisible with the shorter pulse. Tests are needed to determine the conditions when the shorter pulse would be useful.

An additional refinement is to modify the radar circuitry so that the gain function more closely follows the decrease in radar return strength with range to give a better image with a more even contrast across the image and less saturation near the center of the PPI. This will also give an image better suited to automatic analysis procedures.

If a large quantity of data is collected with these radar systems, then automated methods are needed for analysis. Suggested methods include (a) Fourier transforms of the radar film using either optical or digital methods, (b) analytical means for obtaining wave direction from the direct radar return signal, and (c) a TV recording system in lieu of

the 16-millimeter film may permit improvement in the original settings of some of the console controls and may facilitate automatic data analysis routines.

The CERC radar is being tested at the CERC Field Research Facility (FRF) at Duck, North Carolina, where wave height spectra are available from a number of other sensors (including a waverider buoy) within the radar field of view. Windspeeds and wave spectra at FRF present an opportunity to better define the minimum conditions to obtain wave images. A study of the quality of wave images for various wave heights, wave periods, and windspeeds is needed. Since the radar-scattering capillary waves are enhanced due to the curvature of the gravity waves, a stronger return would be expected from the steeper waves. Thus, the minimum conditions for wave imagery would probably be a function of wave height and wavelength. Antenna height also has an impact on whether particular wave conditions can be imaged. Although images have been obtained for wave heights of 1 meter or greater for most conditions and often for waves of smaller height, these future tests should provide the quantities of data necessary to precisely establish limits on the conditions suitable for radar wave imagery.

These tests at FRF will also present an opportunity to study the relationship between radar return and wave height. An "A-scope" display will be inserted into the radar system to show the return along a particular azimuth where the display is similar to that of an oscilloscope with the vertical axis representing the magnitude of the radar return and the horizontal giving the range to the targets. In the CERC system the return along a particular azimuth will be gated to the A-scope, and will likely be a type of storage oscilloscope. Radar return strength as measured from the A-scope will be compared with the wave spectra for a variety of sea states and wind conditions.

The CERC radar system has been used at Channel Islands Harbor, California, in support of a sediment study and to obtain wave imagery as part of the West Coast Experiment. This system has been moved to Duck, North Carolina, to further develop the system's capabilities and to support research projects at the FRF. The unit will also be available to support CERC or U.S. Army Engineer Districts in projects involving wave imagery.

VIII. SUMMARY

This report has shown that images of the most prominent waves on the sea surface can often be obtained with the aid of commercially available marine navigational radar. Images of the wave field are collected by photographing the display scope of the radar. Records may be obtained in an unattended mode by a programing device which activates the system and collects a sequence of photos at fixed-time intervals. Wave direction at a fixed point or the prevailing wave direction for a designated area may be determined by inspecting the photos.

Comparisons of estimates of wave direction and wavelength (based on radar photos with estimates from other imagery, including aerial photos and gage records) generally show good agreement.

Although the quality of radar imagery is not as good as that of aerial photography, it has the advantage of being available at night and during storms. Radar also permits images of the wave field to be collected in the time-lapse mode and is less expensive than aerial photography. Radar images have a distinct advantage over an array of wave gages as a source of information on wave direction because the radar image provides visual evidence of refraction (when present) and of the relation between wave direction in the designated region and the surrounding area.

The radar imaging technology in determining wave direction has some distinct restrictions to be recognized if this technique is to be properly explored.

The most fundamental limitation is the need to have ripples (at least 1.5 centimeters in length) coexisting with more prominent wave trains to obtain sufficient signal return. However, a windspeed of 5 knots will generally assure sufficient ripple formation. Thus, this condition is usually satisfied in a growing wave field.

The resolution of commercial radars is not adequate to ensure detection of wavelengths less than about 25 meters (83 feet) corresponding to periods of 4 seconds in deep water. However, slightly shorter waves may be distinguished on occasion. This restriction can be reduced by redesigning some components of the radar system.

The contrast between the appearance of the wave crest and wave trough is greatest when the wave crest is high enough relative to the radar antenna to shadow the following trough, but not high enough to shadow the following crest. For most coastal locations an antenna elevation between 10 and 20 meters is best, although a variable antenna height could be more useful.

The optimum console settings vary with the ambient conditions of wind and waves. Some allowance for this factor has been made in the CERC system by photographing the display scope with a series of ranges during each observation. A median level for the other console settings to achieve the best imaging in most conditions has been determined.

Radar images generally indicate long-crested waves with characteristics which change only slowly in time. A slight variability in intensity and direction is apparent along each crest, but the general pattern is usually stable.

This report has shown that high-resolution imaging radar is a useful tool in the study of waves in the coastal zone, and that this approach is more useful than other alternatives for some applications. Many years of research and development are required before most of the questions on the use of imaging radar in the study of waves can be answered.

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